THE UNIVERSITY OF ALBERTA

THE RELATIONSHIP OF SOUTHWARD DRIFTING AURORAL

ARCS TO THE MAGNETOSPHERIC ELECTRIC FIELD AND

SUBSTORM ACTIVITY

by

(C)   SAVITHRI SUBBARAO

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled THE RELATIONSHIP OF SOUTHWARD DRIFTING AURORAL ARCS TO THE MAGNETOSPHERIC ELECTRIC FIELD AND SUBSTORM ACTIVITY, submitted by Savithri Subbarao in partial fulfillment of the requirements for the degree of Master of Science

ABSTRACT

The magnitude of the westward directed auroral
zone electric field is inferred from the measurement
of the southward drift of moderately bright auroral
arcs. In a sample of 43 events recorded over a period
of 15 months at Fort Smith (68.1^{o}N geomagnetic) it was
found that southward drifting arcs were predominantly
associated with the decay phase of polar magnetic sub-
storms, and no evidence was found for the association
of southward drifting arcs with the so-called growth
phase of substorms. It is suggested that the southward
drifting arcs are generated through the precipitation
of energetic plasma affected by the limit on stably
trapped particle fluxes proposed by Kennel and Petschek
(1966).

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Structure of the Magnetosphere

The interaction of the solar wind with the Earth's magnetic field results in the distortion of the dipolar structure of the magnetic field, compressing it on the solar side and extending it on the anti-solar side to form the magnetotail. The various parts of the magneto- sphere (the name given to the distorted magnetic field configuration) are shown in Figure 1.1. The magneto- sphere is populated with energetic charged particles (found mainly in the belts of trapped radiation) and thermal plasma (found in the plasma sheet extending into the magnetotail, and in the plasmasphere).

The particles in the magnetotail experience convec- tive drift motion arising from the gradients in the magnetic field of the tail, as well as from the electric field which is usually directed across the tail from dawn to dusk. The inner boundary of the convection pattern of the particles can also be identified with the boundary of the plasmasphere (termed the plasmapause). The pro- jection of the outer boundary of the trapping region along the geomagnetic field lines to the ionosphere corresponds approximately with the auroral oval, which is defined as the instantaneous locus of auroral activity. This is thought to be the case since the energetic particles in

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MAGNETOSPHERE AND TAIL

QUASI-TRAPPED   PLASMA SHEET   NEUTRAL SHEET

ORBIT OF MOON

GEOMAGNETIC EQUATOR

MAGNETOPAUSE

SOLAR WIND

TURBULENT MAGNETOSHEATH

SHOCK WAVE
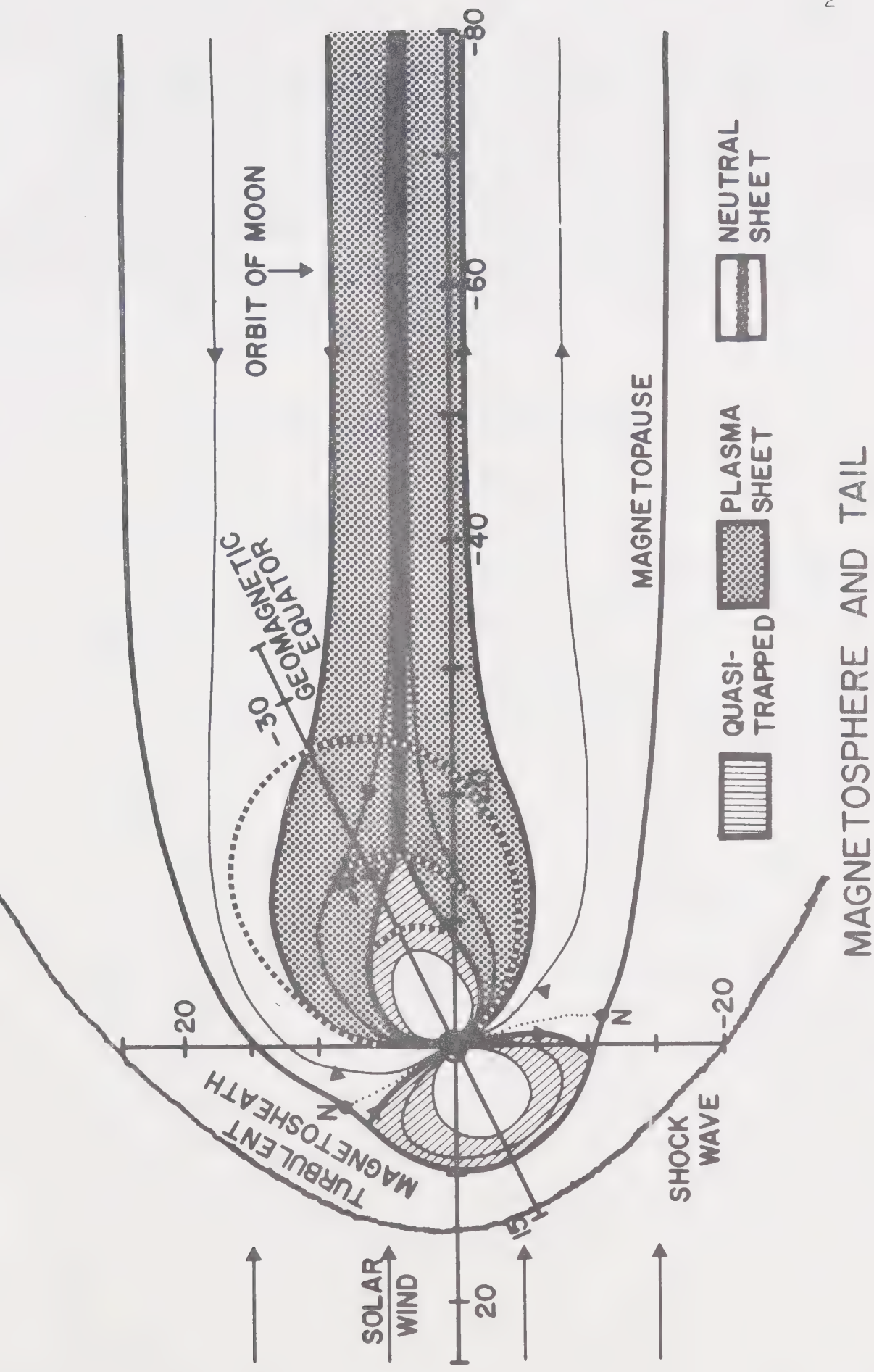
Figure 1.1

the trapping region are the ones that are eventually
precipitated to cause auroras. It is important to
understand the behaviour of these energetic particles
under the action of electric and magnetic fields in
order to gain some insight into the method by which
auroral activity is generated.

1.2 Drifts of Trapped Charged Particles

Let us now consider the motions to which the
trapped particles are subject (Roederer, 1970). A
charged particle in the presence of the Earth's magnetic
field will in general experience three types of motion,
namely, a cyclotron motion, a bounce motion, and a drift
motion along a closed surface bounded by field lines.
These three types of motion are governed respectively
by the first, second, and third adiabatic invariants.

We first consider the cyclotron motion. For the
purposes of this discussion we use the guiding centre
approximation, and define the guiding centre system (GCS)
as a moving frame of reference in which, at any instant
of time, an observer sees the particle in a periodic orbit
perpendicular to the direction of the magnetic field.
The particle's motion can then be described in terms of
the displacement of the guiding centre, with the particle
in cyclotron motion about the guiding centre; the

instantaneous velocity of the guiding centre is defined to be the velocity of the GCS.

For a particle in a uniform static magnetic field under the influence of an external nonmagnetic force $\underline{F}$ (constant in space and time), the equation of motion can be written as

$$\frac{d\underline{p}_{||}}{dt} = \underline{F}_{||} \tag{1}$$

$$\frac{d\underline{p}_{\perp}}{dt} = \underline{F}_{\perp} + q \, \underline{V}_{\perp} \times \underline{B} \tag{2}$$

the parallel and perpendicular directions being defined with respect to the magnetic field direction.

The first of these equations gives the parallel velocity of the particle and the GCS, $V_{||}$. The perpendicular, or drift velocity $\underline{V}_F$ of the GCS is given by the instantaneous velocity of a reference frame in which the particle executes its cyclotron motion. In this reference frame, the external force $\underline{F}_{\perp}^{*}$ ($= \underline{F}_{\perp}$) (starred symbols refer to quantities in the GCS) will be balanced by the induced electric field force:

$$q \, \underline{E}^{*} = q \, \underline{V}_F \times \underline{B} \quad . \tag{3}$$

Therefore, we have that :

$$q \, \underline{V}_F \times B = - \underline{F}_{\perp} \tag{4}$$

$$\frac{\underline{B}}{qB^2} \times q(\underline{V}_F \times \underline{B}) = - \frac{\underline{B}}{qB^2} \times \underline{F}_\perp \qquad (5)$$

$$\underline{V}_F = \frac{\underline{F}_\perp \times \underline{B}}{qB^2} \qquad . \qquad (6)$$

This is the zeroth order, or force, drift of the particle. Outside the GCS, the particle has a cyclotron motion, a translation with constant velocity $\underline{V}_F$, and a translation parallel to the field line. Note that equation (6) above is non-relativistic, the condition for its validity being:

$$\frac{F_\perp}{qB} < c \quad . \qquad (7)$$

If the external force is not constant in space, but is given by the gradient of a scalar potential:

$$\underline{F} = - \nabla U \qquad (8)$$

condition (7) becomes:

$$\nabla U \rho_c << T \qquad (9)$$

where ρ_c is the Larmor radius of the particle, and T its kinetic energy. This leads to the restriction:

$$V_F << v \qquad (10)$$

where v is the particle's velocity.

Now suppose the particle is in a non-uniform magnetic field. The gradient of the field can also be written as a sum of two components, $\nabla_\perp B$ and $\nabla_\parallel B$. First consider only the perpendicular gradient. Its effect will be to cause an alternating change of the Larmor radius in the particle's orbit. This change acts in the same way as a net Lorentz force directed oppositely to $\nabla_\perp B$. The cyclotron average of this net force, R , is:

$$R = \frac{1}{2} q\, v_\perp\, \nabla_\perp B\, \rho_c \, . \tag{11}$$

This force has an associated drift, as has just been derived (eq. (6)), given by:

$$\underline{V}_G = \frac{1}{2} \, \frac{m v_\perp{}^2}{q B^2} \, \underline{B} \times \underline{\nabla}_\perp B \tag{12}$$

under the condition that:

$$\rho_c \, \frac{\nabla_\perp B}{B} \ll 1 \, . \tag{13}$$

This condition may also be written as

$$V_G \ll v_\perp \, . \tag{14}$$

The gradient drift is therefore a first order drift.

There is a further first order drift, due to the curvature of the magnetic field lines. The radius of curvature of the field line is given by

$$R_C = \frac{B}{\nabla_\perp B} \quad . \tag{15}$$

Assuming in the first approximation that the guiding centre follows the curved field line subject to the condition $R_C \gg \rho_c$, we find that the GCS will be a non-inertial system; any mass m in it will thus experience an inertial (centrifugal) force:

$$\underline{F}_C = \frac{mv_{||}^2}{R_C} \, \hat{n} \tag{16}$$

where $\hat{n}$ is the unit normal directed along the radius of curvature of the field line. This force also causes a drift, given by:

$$\underline{V}_C = \frac{mv_{||}^2}{qR_C B^2} \, \hat{n} \times \underline{B} \quad . \tag{17}$$

Since, for a curl-free field,

$$\underline{\nabla}_\perp B = - \frac{B}{R_C} \, \hat{n} \tag{18}$$

the curvature drift can be rewritten:

$$\underline{V}_C = \frac{mv_{||}^2}{qB^3} \, \underline{B} \times \underline{\nabla}_\perp B \, . \tag{19}$$

Since both the curvature drift and the gradient
drift are in the same direction and always appear
together, we can write the total first order drift
as:

$$\underline{V}_{CG} = \frac{m}{2qB^3} (v_{\perp}^2 + 2v_{||}^2) \underline{B} \times \underline{\nabla}_{\perp} B \quad . \qquad (20)$$

If the zeroth or first order drifts are time de-
pendent, second order drifts also appear. In this case,
a frame of reference which moves with a zero or first
order drift $\underline{v}$ will be accelerated, and an inertial force
$-m\underline{\dot{v}}$ is observed in that reference frame. Hence, the
GCS must move with a velocity $\underline{V}$ plus an additional drift
velocity generated by the inertial force, given by:

$$\underline{V}_S = - \frac{m}{qB^2} \underline{v} \times \underline{B} \quad . \qquad (21)$$

For the guiding centre approximation to remain valid,
the condition:

$$\frac{\tau_c \dot{V}}{V} << 1 \qquad (22)$$

must be satisfied, where τ_c is the cyclotron period of
the particle.

The general expression for the drift velocity of
a particle in a non-uniform magnetic field, under the
influence of an external non-magnetic force, can be

obtained by combining the zeroth, first, and second
order drifts, to be

$$\underline{V}_D = \frac{\underline{B}}{qB^2} \times [-\underline{F} + \frac{m}{2B} (v_\perp^2 + 2v_{||}^2) \, \underline{\nabla}_\perp B + m\underline{\dot{V}}_D]. \quad (23)$$

1.3 The Magnetospheric Substorm

The auroral substorm is part of a magnetospheric
substorm (Akasofu, 1968). A magnetospheric substorm
usually begins when a southward component of the inter-
planetary magnetic field causes magnetic field merging
on the dayside magnetosphere. Some of the magnetic flux
resulting from the merging is transported by the solar
wind to the magnetotail. During the transfer process,
polarization of the magnetospheric plasma produces an elec-
tric field in the magnetosphere. The effect of this elec-
tric field mapped into the ionosphere is to generate iono-
spheric electric currents; in particular, it generates
the auroral electrojet , a concentrated electric current
induced along a section of the auroral oval. The magne-
tic disturbance generated by the auroral electrojet and
the motions of the protons in the magnetosphere consti-
tute the polar magnetic substorm, which occurs in con-
junction with the auroral substorm.

The auroral substorm is defined (Akasofu, 1964) as
the sequence of events starting with quiet auroral

conditions, through various phases of activity, to a reversion to quiet conditions.

The seven stages of the auroral substorm can be broadly classified into three phases. During the quiet phase, quiet, homogeneous arcs are present in the midnight sector of the auroral zone. Next is the expansive phase, in which one of the arcs, usually the one farthest equatorward, suddenly brightens. The sudden brightening is usually followed by rapid poleward expansion, resulting in the formation of a bulge around midnight which rapidly expands poleward, westward, and eastward. This process continues until the front of the expanding bulge reaches its most poleward position at which time a westward surge may be seen to develop and move towards the evening sector. This marks the end of the expansive phase. During the recovery phase, the intensity of the arcs diminishes and they begin to drift equatorward, over a wide range of latitude and longitude, until quiet-time conditions are again established. During the initial part of the recovery phase weak loops and folds in the arc structure are seen at the poleward edge of the activated auroral region. The various stages described above are summarized in Figure 1.2.

1.4 Purpose of Thesis

The convection process occurring in the magnetosphere can be considered as a first approximation to be
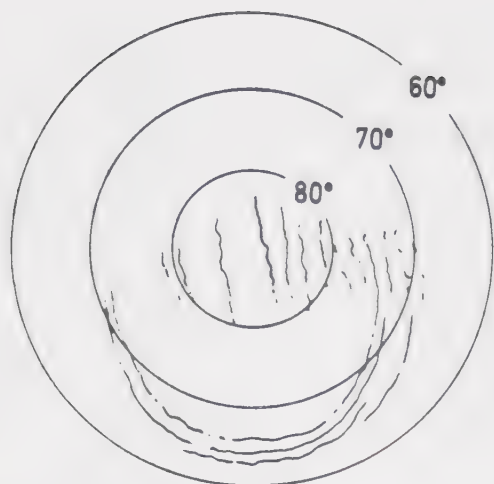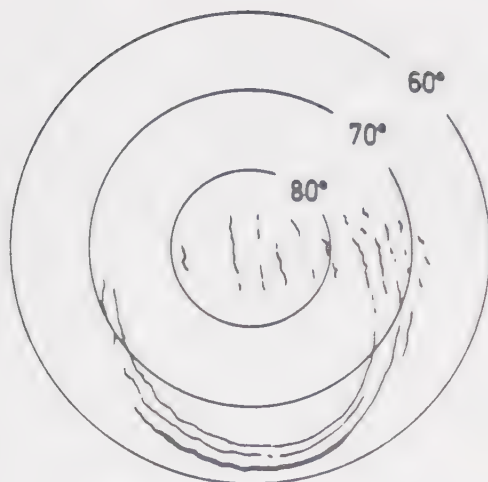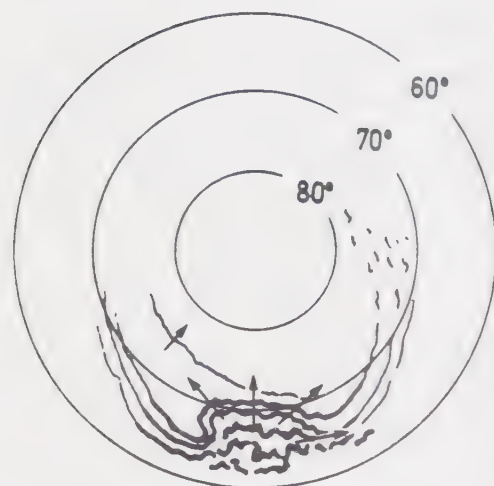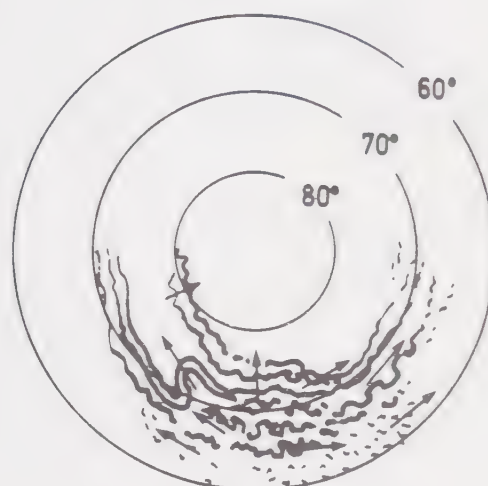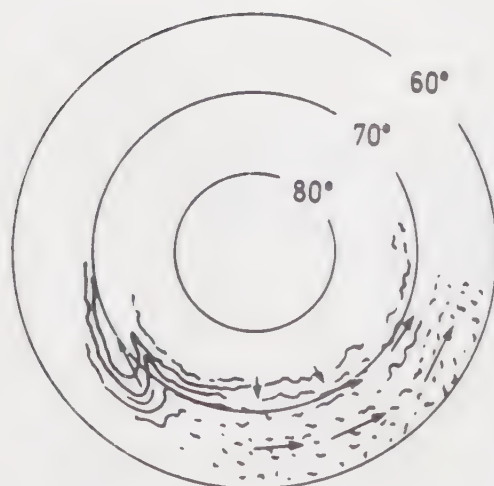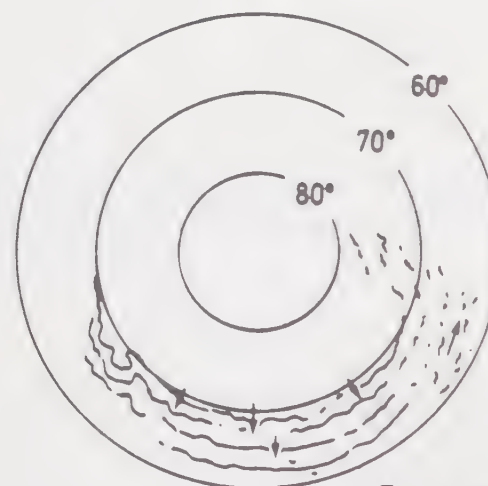
Figure 1.2

described by steady-state convection, that is, $\partial \underline{B}/\partial t = 0$.
Hence, the second order drifts in equation (23) can be
neglected. The zeroth and first order drifts of parti-
cles in the presence of the enhanced dawn-to-dusk elec-
tric field, which causes the growth of the asymmetric
ring current during a magnetospheric substorm, are shown
in Figure 1.3. We see that the zeroth order drift is
directed towards the Earth, while the first order drift
is in the azimuthal direction. Hence, the velocity of
inward convective drift of the charged particles is given
by the zeroth order drift, viz:

$$\underline{V}_D = \frac{\underline{E} \times \underline{B}}{B^2} \quad . \tag{24}$$

The magnitude of the electric field can thus be calculated
by obtaining the inward drift velocity of the particles,
and using the relation

$$E \cong V_D B \quad . \tag{25}$$

One of the purposes of this thesis is to obtain values of
the ionospheric electric fields during periods of auroral
activity in the manner described above.

An important contribution will be made from the
study of the phase of the associated magnetic substorm
during which the auroral arcs were observed. The growth
phase of a magnetic substorm (McPherron, 1970) may or
may not be accompanied by the presence of equatorward
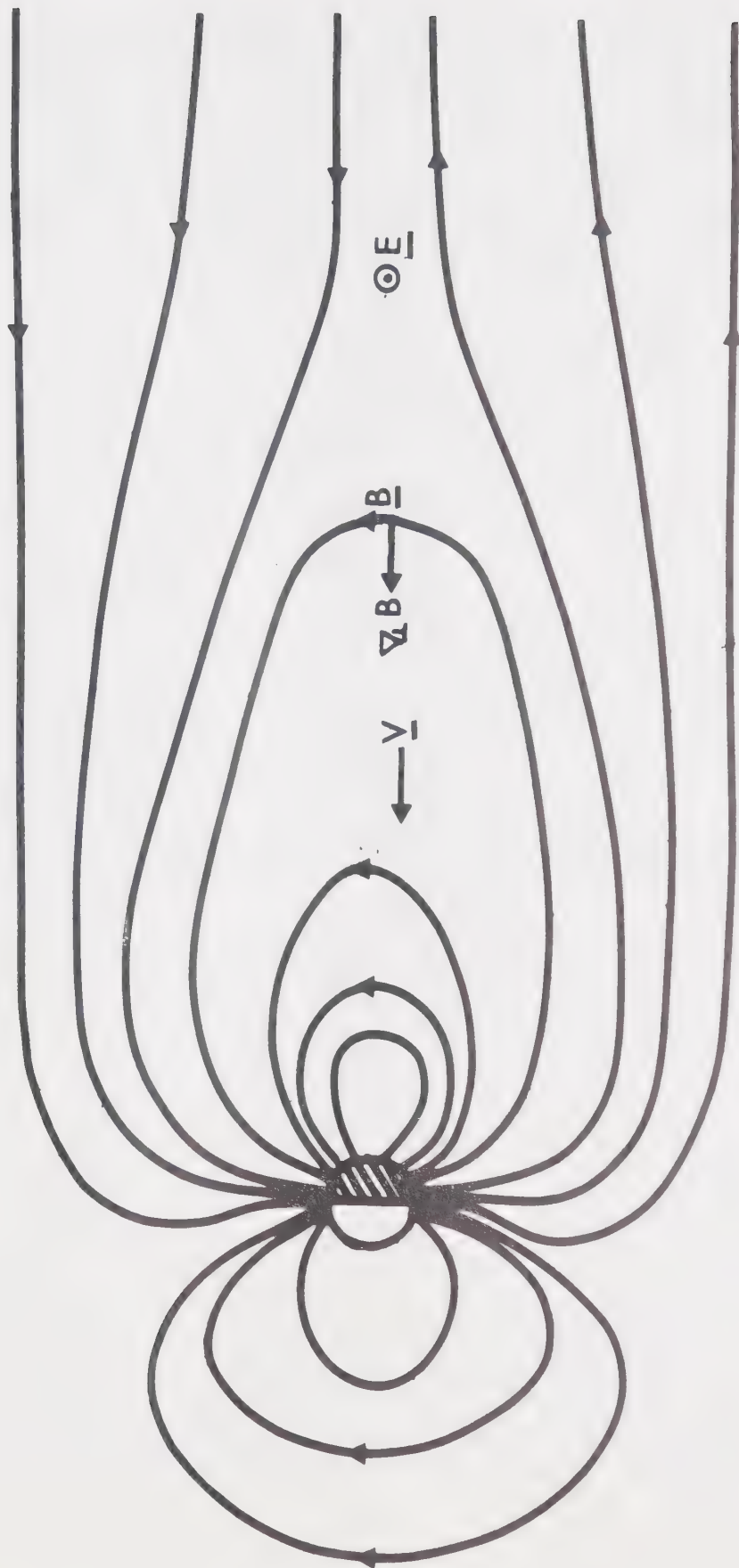
Figure 1.3

drifting arcs, as claimed by Mozer (1971) and Feldstein (1972), however such drifts definitely occur during the recovery phase of the magnetic substorm (Akasofu, 1964). The problem then arises as to whether an observation of equatorward drifting arcs indicates the presence of a growth phase or a recovery phase. This ambiguity will be discussed during the course of this investigation and an explanation is put forward, using a modified version of a theory of the generation of equatorward drifting auroral arcs proposed by Atkinson (1970). This theory is based on the theory of resonant wave-particle inter-actions (Kennel and Petschek, 1966). Such a mechanism has been used to explain the production of SAR arcs (Cornwall et al, 1971) and the precipitation of Van Allen drift particles in the morning hours (Brice and Lucas, 1971).

2.   DETAILS OF THE ANALYSIS

2.1   The All-sky Camera

We have established (eq. 25) that the relationship between the convective drift velocity of particles, V_D, and the associated magnetospheric electric field in the equatorial plane is given by:

$$E \simeq V_D B$$

where B is the strength of the ambient magnetic field in the equatorial plane.

This same relationship also holds in the ionosphere, where the quantities involved are the equatorward drift velocity of the magnetic flux tube, the ambient magnetic field in the auroral ionosphere, and the associated ionospheric electric field. The details of the mapping of auroral drift velocities in the ionosphere to convective drift velocities in the equatorial plane, are discussed in the next section.

The drift velocity of the auroral arcs was calculated using all-sky camera (ASCA) photographs from a station at Fort Smith, N.W.T. ($68.1^{O}N$ corr. geomag.). ASCA photographs covering intervals during 1970 and 1971 were studied, over a total sample size of fifteen months. The film data consisted of eight second exposures taken
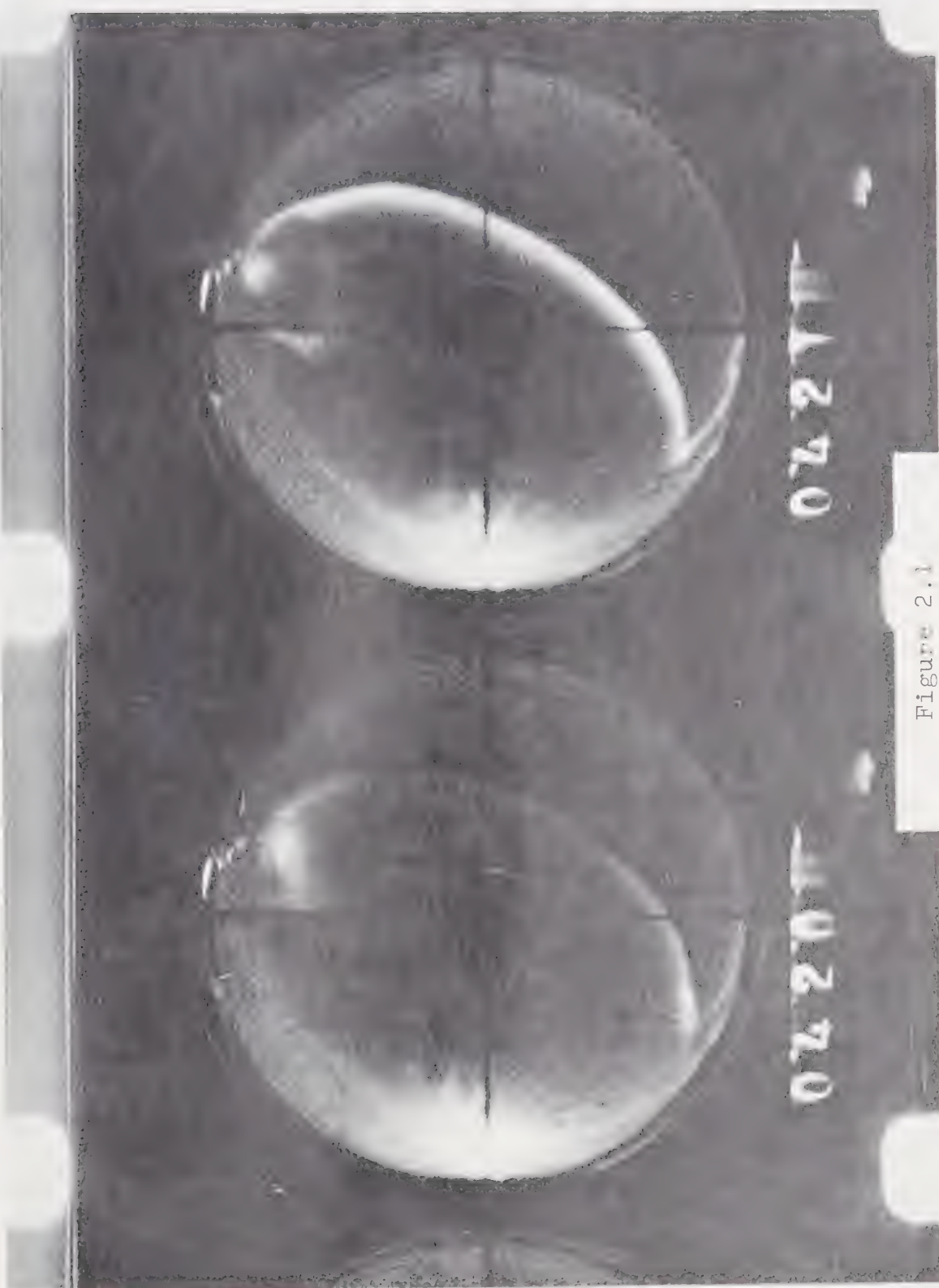
Figure 2.1

at one minute intervals, at a setting of f 0.95 and using
Kodak Tri-X reversal black and white film. A typical
ASCA photograph illustrating the form of the data is shown
in Figure 2.1.

The eight-second exposure time has an integrating
effect on the position of the arcs - that is, motion of
an arc during the exposure time is undetected by the
camera. To overcome this hurdle, only the motion of the
northern or southern boundary of the arc form was followed
in successive frames. In addition, the one-minute interval
between exposures creates an ambiguity regarding the drift
motion of the arcs. We are faced with the question of
whether the apparent southward drift of an arc is an
actual motion, or the result of the decay of one arc and
the establishment of a second arc at a new, more southern
position. There is no absolute method of resolving this
ambiguity, but it can be reduced to a minimal level by
adopting certain criteria in the selection of events for
study. The primary criterion was that only those arcs
which could definitely be identified as being in motion
for a minimum of three frames (i.e. three minutes) were
chosen for analysis.

One side effect of the three minute criterion is
that many events of short duration were ignored. This
fact, together with the possibility that arcs may have

appeared whose brightness was below the threshold sen-
sitivity of the film, had the cumulative effect of
reducing the total number of events treated. In all,
forty-three cases of southward drift of auroral arcs
were identified over the sample interval. We feel that
the reasons given above adequately explain the low
number of events, in comparison with the number of
southward drifting events noted by other workers (e.g.
Davis, 1962).

For the purpose of analysis, the arcs were first
traced from the film onto ASCA analysis sheets (see
Figure 2.2), and then mapped onto a linear scale to
eliminate the curvature effect provided by the primary
mirror of the ASCA. The mapping was done by means of
an auroral arc mapper. The mapper is a template (see
Figure 2.3), on which holes are drilled at closely spaced
points along two curved loci. Each of the holes on the two
loci is connected to a point on the inside edge of the
template by a straight line, as shown in the figure. Each
of the edge points connected to the holes is superposed in
turn on the auroral arc positions on the tracing, and the
hole position is marked. The position of the hole corres-
ponds to arc position on a linear scale. The mapped points
are then joined to obtain the form of the mapped auroral arc.
The velocity of southward drift was determined from the suc-
cessive positions of the mapped arcs (Figure 2.4). The technique

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Figure 2.2

outer curve

inner curve

Figure 2.3

AURORAL ARCS

FORT SMITH (68.1 N)
OCTOBER 29, 1971

100KM
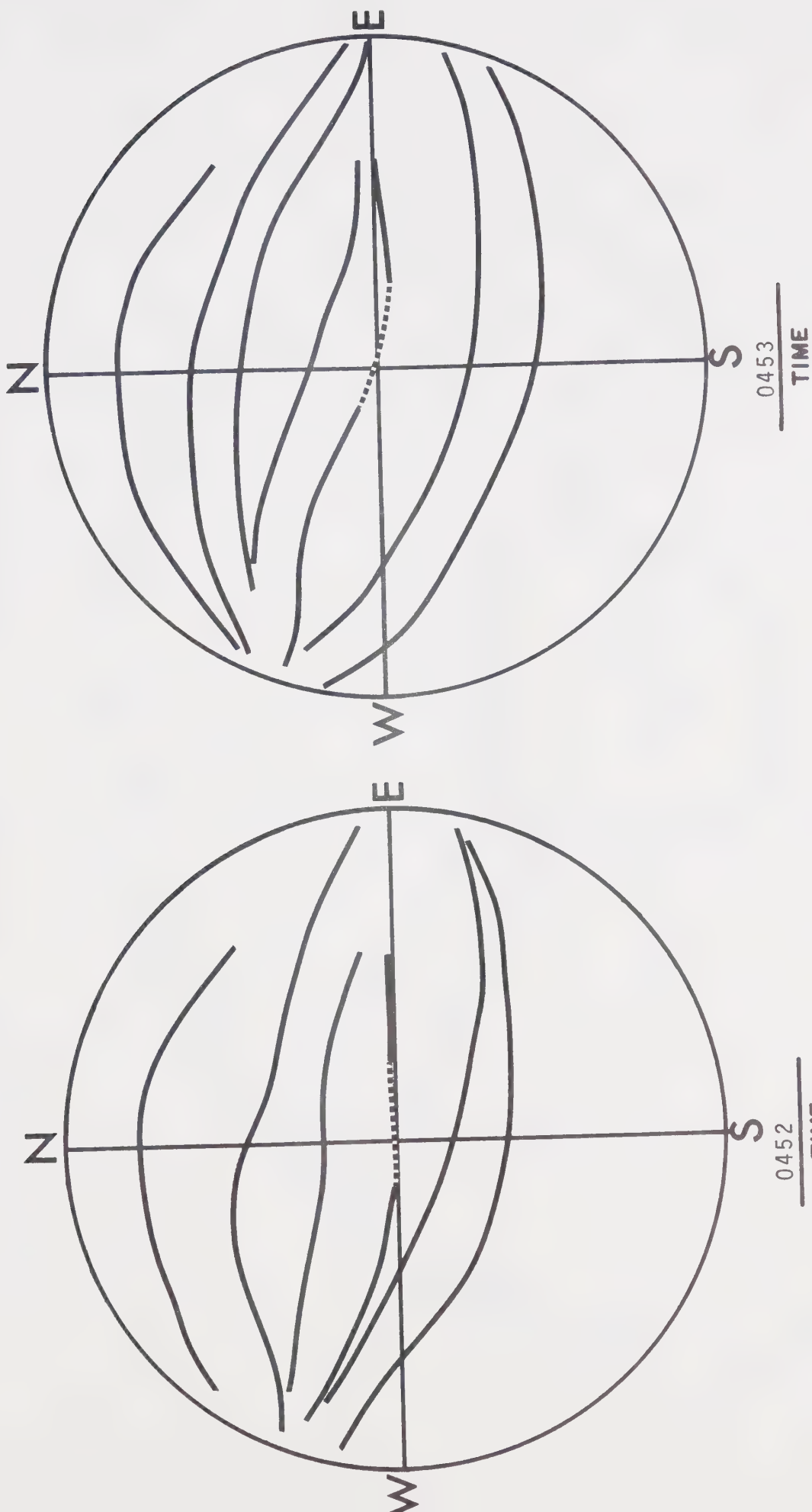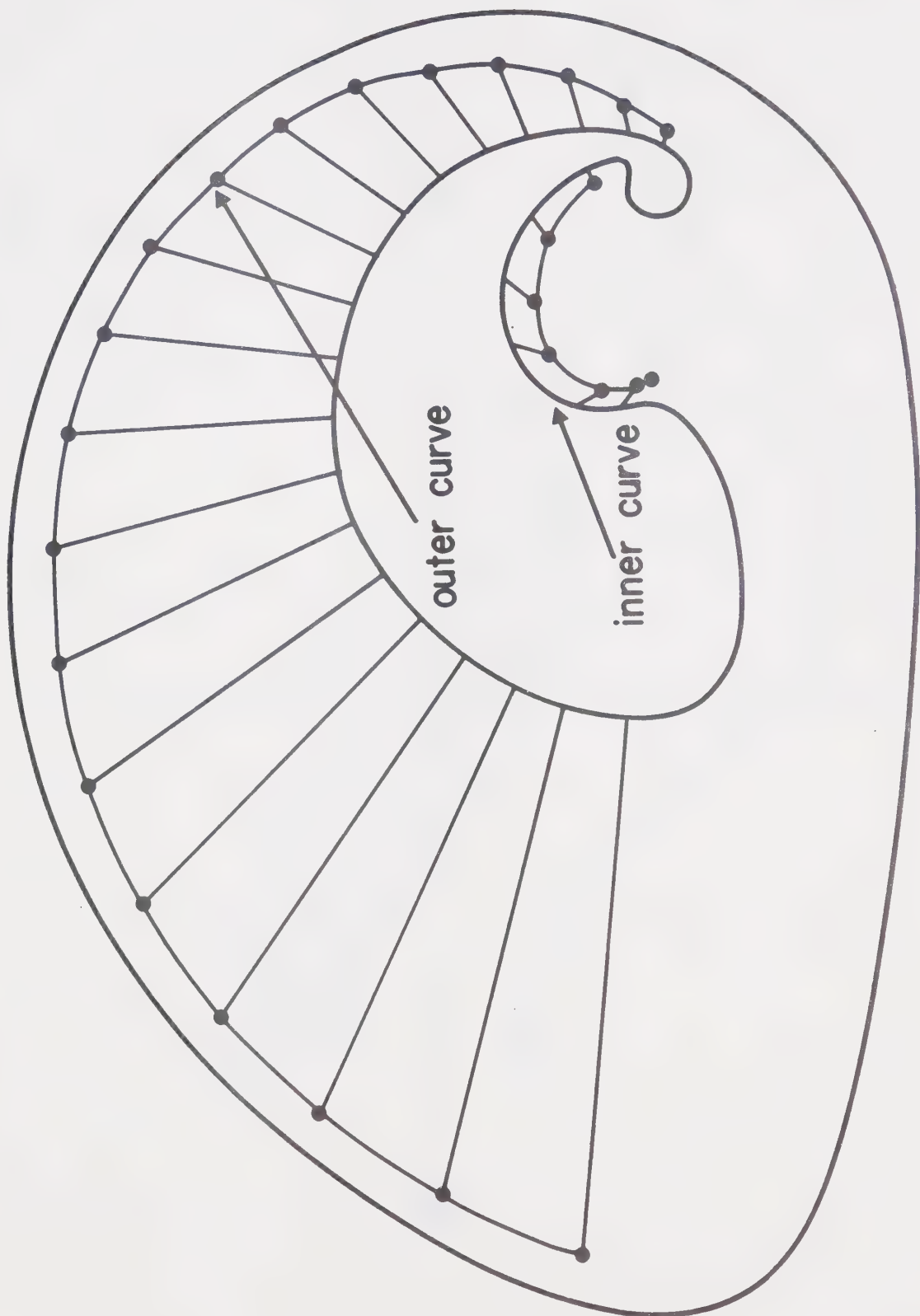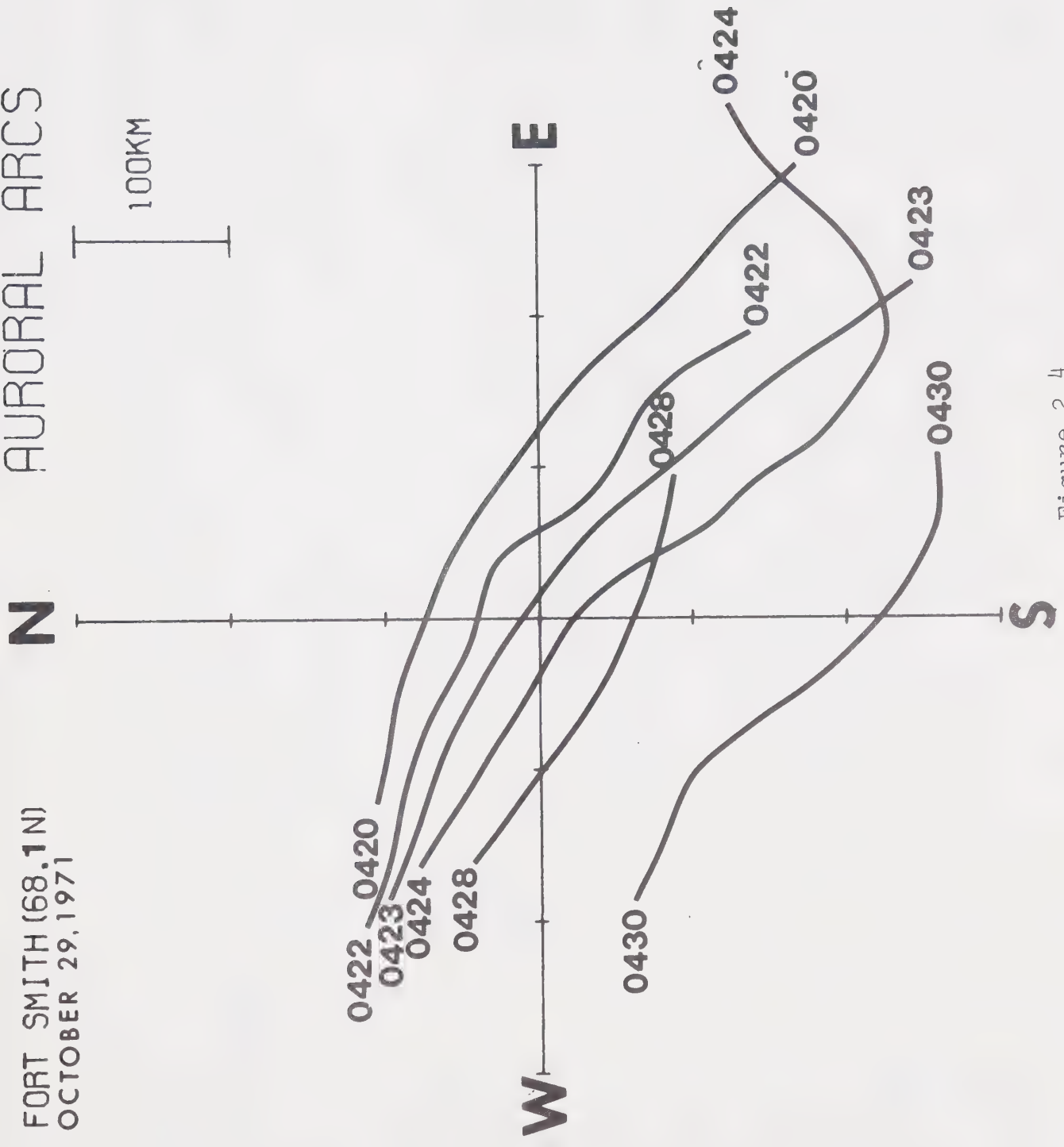
Figure 2.4

of inferring convective motion in the magnetosphere from the drift velocity of auroral arcs has been used previously by several workers (e.g. Davis, 1971; Kelley et al, 1971).

2.2 The Mapping Factor

The velocity obtained from the motion of the mapped arcs is the drift velocity of the arcs in the ionosphere. The value of the electric field that is eventually determined is also the ionospheric value. However, we also wish to compare the value of the electric field in the equatorial plane, as obtained from this method, with the values obtained by other means. It is therefore necessary to have a mapping factor between the ionosphere and the equatorial plane. The velocity thus obtained in the equatorial plane is an indication of the convective drift velocity of particles in that region. The mapping factor has been calculated by Mozer (1970), and is given by the ratio of the westward electric field in the ionosphere to that in the equatorial plane.

$$\frac{E_{Wi}}{E_{We}} = L^{3/2} \quad .$$

The L value corresponding to Fort Smith is ~7; this gives a value of 18.5 for the mapping factor. The mapping

factor for velocities, then is given by:

$$\frac{V_e}{V_i} = 18.5 \quad .$$

It should be pointed out that this mapping assumes a dipolar magnetic field in the absence of parallel electric fields. Such a situation does not occur often in reality, and the effects of deviations from the ideal ought to be examined. The non-dipolar character of the field lines in the nightside magnetosphere does not alter the basic law of conservation of magnetic flux, which is the underlying principle in the theory of the mapping. It does, however, alter the geometry of the field, and thus the mapping factor from the magnetosphere to the ionosphere is affected. Hence, the final value of the mapping factor may be different from $L^{3/2}$, by some factor depending on the magnitude of the distortion of the field from the dipolar configuration. Even if this were not the case, the change in L value as the arcs move equatorward may contribute a significant error.

If parallel electric fields are present, there will be a potential drop along the field line from the magnetosphere to the ionosphere. If the potential drop is the same along neighbouring field lines, then the expression for the mapping factor still remains valid. This implies that there should not be much longitudinal variation in the electric field.

It is difficult to know quantitatively how well these conditions for validity are met. Because of this difficulty the effect of these errors cannot be accurately incorporated into the calculations done here. However, their presence certainly ought to be recognised.

2.3 Magnetic Data

The magnetic effects associated with the events under analysis were studied to determine the phase of the polar magnetic substorm corresponding to the time of appearance of southward drifting arcs. This question is of some importance since some workers have claimed that southward drifting arcs are associated with the growth or development stage of the associated polar magnetic substorm (Belyakova et al, 1968; Feldstein, 1972; Mozer, 1971). It has also been claimed that the growth phase has a ground-based magnetic signature (McPherron, 1970).

We have therefore approached this problem by examining the ground-based magnetic records associated with our events using all auroral zone stations in the North American sector. A list of these stations and their geomagnetic co-ordinates is given in Table 2.1. To identify the phase of the associated magnetic substorm, a tentative phase was assigned to the substorm at each

Table 2.1

Coordinates of Magnetic Observatories Whose

Records are Used in This Study

Observatory	Geographic (^{O}N)	(^{O}E)	Coordinates Corr. Geomag. (^{O}N)	(^{O}E)
Used to Determine Phase of Substorm				
Great Whale River	55.3	282.2	68.2	353.8
Fort Churchill	58.8	265.8	70.3	325.9
Baker Lake	64.3	264.0	75.1	320.4
Meanook	54.6	246.7	62.5	301.2
Sitka	57.0	224.7	59.8	276.6
College	64.9	212.2	64.9	260.3
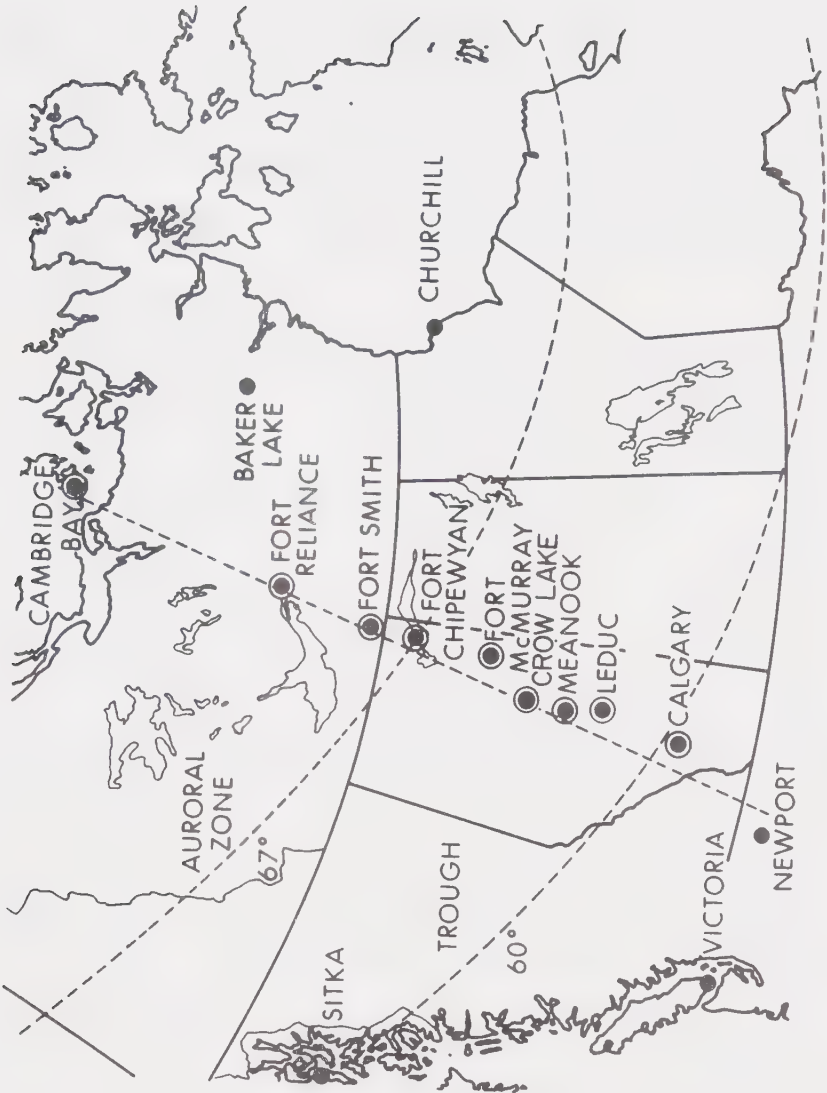
Figure 2.5

station after an independent examination of the station's
magnetic records. Then these assigned phases were com-
pared for each event to determine if the results were
self-consistent. In cases of ambiguity or inconsistency,
the records of the station under question were reexamined,
this time in conjunction with the information available
from the other stations. It will be seen later that in
some cases the ambiguity remained unresolved even after
the reexamination.

In addition, the behaviour of the associated current
systems was also determined, through a study of the corres-
ponding latitude profiles for each event. (See Kisabeth
and Rostoker (1971) for details of latitude profiles.)
The latitude profiles were obtained using the magnetic data
from the University of Alberta line of magnetometer
stations in Alberta and the Northwest Territories. The
stations lie along the corrected geomagnetic meridian
of ~301°E and are closely spaced in the latitude range
58° to 77°N. Supporting data were obtained from the
standard observatories at Newport, Baker Lake, and
Resolute Bay at 55.3^{O}N, 75.1^{O}N and 84.3^{O}N respectively.
The locations and co-ordinates of these stations are
shown in Fig. 2.5 and Table 2.2. A three-component
fluxgate magnetometer operated at each of the stations
along the line, recording the three components (H,D,Z)

Table 2.2

Coordinates of Magnetic Observatories Whose

Records are Used in This Study

Observatory	Geographic (^{O}N)	(^{O}E)	Coordinates Corr. Geomag. (^{O}N)	(^{O}E)
Used to Create Latitude Profiles				
Resolute Bay	74.7	265.1	84.3	306.0
Cambridge Bay	69.1	255.0	77.7	301.0
Fort Reliance	62.7	251.0	71.4	300.0
Fort Smith	60.0	248.0	68.1	300.8
Fort Chipewyan	58.8	248.0	67.0	301.6
Fort McMurray	56.7	248.8	65.0	302.7
Meanook	54.6	246.7	62.5	301.2
Leduc	53.3	246.5	61.2	301.5
Calgary	51.2	245.5	58.7	302.0

of the magnetic perturbation field in digital form on magnetic tape. The sample rate was one data point for each component every two seconds, with the timing accurate to ±0.1 sec. The dynamic range of the system was ±1000γ with a sensitivity of ±1γ. In the latitude profile, the perturbation components (H,D,Z) are plotted for a given instant of time as a function of geomagnetic latitude of the stations. Successive latitude profiles therefore show the development of the current system in time.

3. PRESENTATION OF THE DATA

3.1 Observational Results

The electric field values obtained from the forty-three cases of southward drifting arcs which were identified are summarized in Table 3.1. A detailed table showing the parameters evaluated for each event appears in the Appendix.

The values of the ionospheric electric field obtained here compare favorably with the ionospheric electric field measurements in the auroral zone obtained by different methods, such as balloon borne electric field probes (Mozer and Manka, 1971) and barium cloud techniques (Haerendel and Lüst, 1970). The average value of 16 mV/m for the ionospheric electric field corresponds approximately to a westward directed magnetospheric electric field of ~0.9 mV/m in the equatorial plane at $L \simeq 7$. This is nearly an order of magnitude greater than the values obtained through whistler techniques (Carpenter et al, 1972); however, their whistler measurements were made at L values corresponding to locations inside the plasmasphere. The fact that the ring current may shield the plasmasphere from the electric fields outside the plasmapause (Vasyliunas, 1971; Chen and Wolf, 1972) mitigates this discrepancy to a large extent. Some error is also introduced from the effect of the Earth's

Table 3.1

Electric Field Values Inferred From Southward
Drifting Arcs

Minimum Value	5	mV/m
Maximum Value	37	mV/m
Average Value	16	mV/m
Standard Deviation	±7	mV/m

Table 3.2

Summary of Magnetic Correlation

Number of southward drifting arcs in sample	43
Magnetic signatures during event:	
No activity	1
Recovery phase (in whole or in part)	34
Expansive phase onset (in whole or in part)	7
Not definitely identifiable phase of sub- storm (in whole or in part)	23
Growth phase	0

rotation under the auroral oval during the evening sector
(Akasofu et al, 1966). Akasofu and his colleagues have
calculated that on the average, the rotation of the Earth
under a stationary oval gives rise to an apparent drift
velocity of 40-50 m/sec. This would correspond to a
magnetospheric electric field value of ~0.08-0.1 mV/m.
Although this is not a large value, it should be noted
that this error is present in most of the values of the
electric field obtained, since most of our events occurred
in the evening sector (see Appendix).

It is interesting to note that the equatorward drift
velocity distribution obtained by Akasofu et al (1966)
has a peak in the range 100-250 m/sec; a similar distri-
bution for our results shows a peak in the range 400-600
m/sec.

Table 3.2 shows, in summary, the correlation
between equatorward drifting arcs and the level of
magnetic activity recorded at auroral zone stations,
as described in section 2. The term "in whole or in
part" which appears in this table is indicative of
either cases where different phases appeared to be
in progress at the different stations, or cases where
it was impossible to definitely identify the phase of
the substorm. However, it can be stated that none of
the ambiguous cases were associated with a growth phase,

including the 23 cases for which no definite phase could be assigned. In fact all but one case occurred within intervals of clear substorm activity, and as the one case when no substorm was in progress, no substorm activity followed the time when the southward drifting arcs were observed. Hence, none of the 43 events identified was associated with pre-substorm effects (or a growth phase) while the great majority of cases (namely 34 of 43) were associated with the recovery phase of the polar magnetic substorm. We note however that the absence of southward drifting arcs during a growth phase does not imply the absence of an enhanced westward electric field in the ionosphere during the pre-substorm period (Kelley et al, 1971).

The latitude profiles associated with the events, observed on the meridional line of stations, showed well-defined magnetic perturbation, associated with the appearance of southward drifting arcs; however, the magnitudes of these perturbations were not in general large compared with the magnitude of the substorm within which the perturbation occurred. Some sample events are discussed in the next section; the Appendix gives the profiles for selected events.

3.2 Sample Events

We consider first events 20-24, which occurred on October 9, 1971 during the interval 0250-0330 UT. We

note that events 20 and 21, and 22, 23, and 24 involve multiple arcs (see list of events in Appendix). This type of structure is typical of southward drifting arcs (Akasofu et al, 1966). Figure 3.1 shows the latitude profiles near the beginning and end of events 20 and 21. The very large positive ΔH regime and small negative ΔZ regime indicate the presence of both an eastward and west- ward electrojet. The presence of these two equally strong electrojets is to be expected in the evening sector (Kisabeth, 1972). We note that the boundary between the eastward and westward jets is the site of the arc develop- ment ($\sim 68^{\circ}$N). As the arcs drift southward, so does the boundary between the two electrojets. This is shown very clearly in Figure 3.2, which shows the profiles near the beginning and end of event 22. The double electrojet system continues to the end of the events, as shown by the arc locations in Figure 3.3 (events 23 and 24). We note also the sudden enhancement in the ΔD profile at Fort Reliance (71.4°N and corr. geomag.),shown by means of a differential profile in Figure 3.4 (corresponding to event 24). A large negative ΔD is indicative of an enhanced convection across the polar cap; such an enhancement is not unreasonable under the circumstances, i.e. during an auroral substorm.
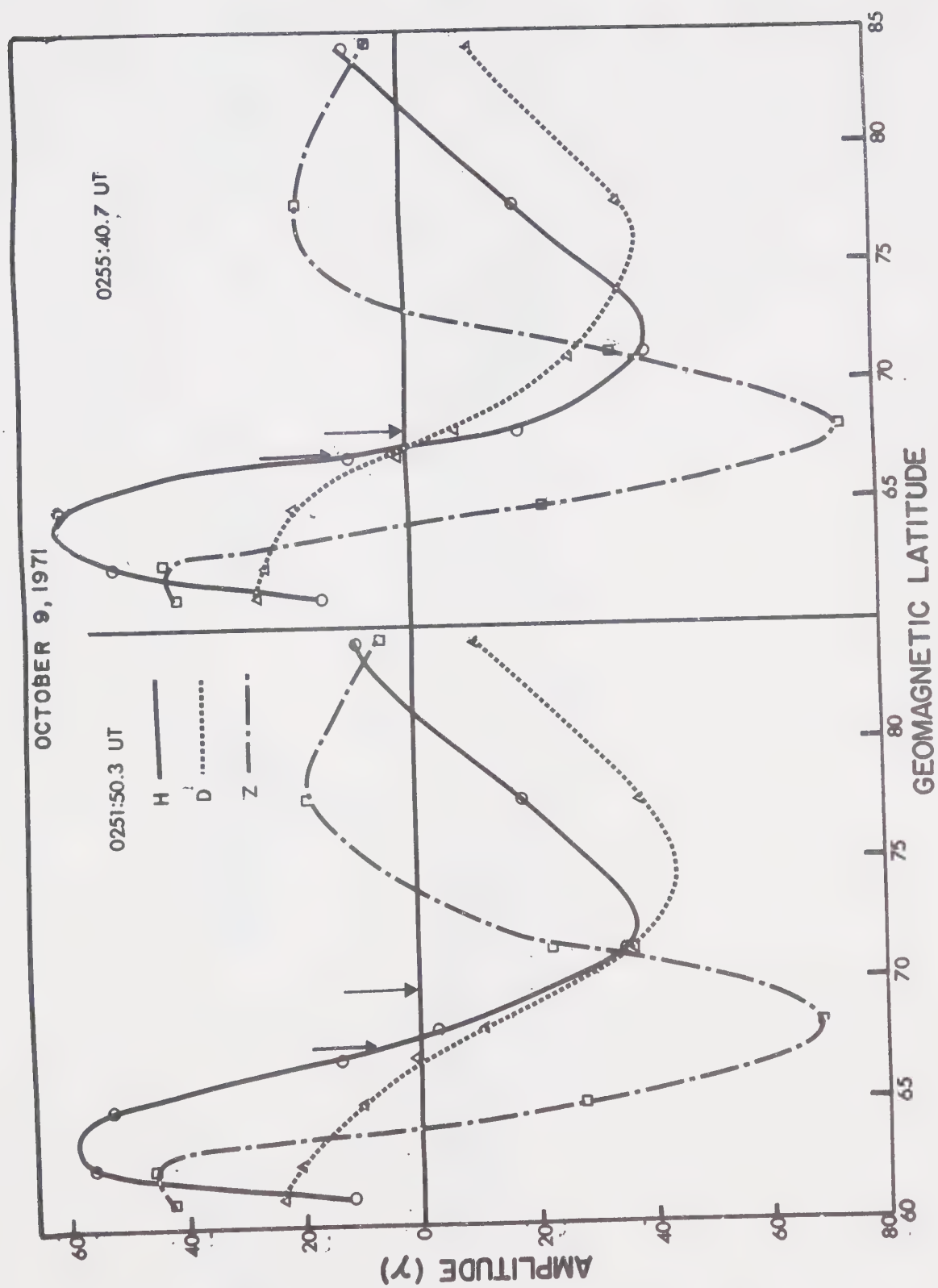
Figure 3.1a
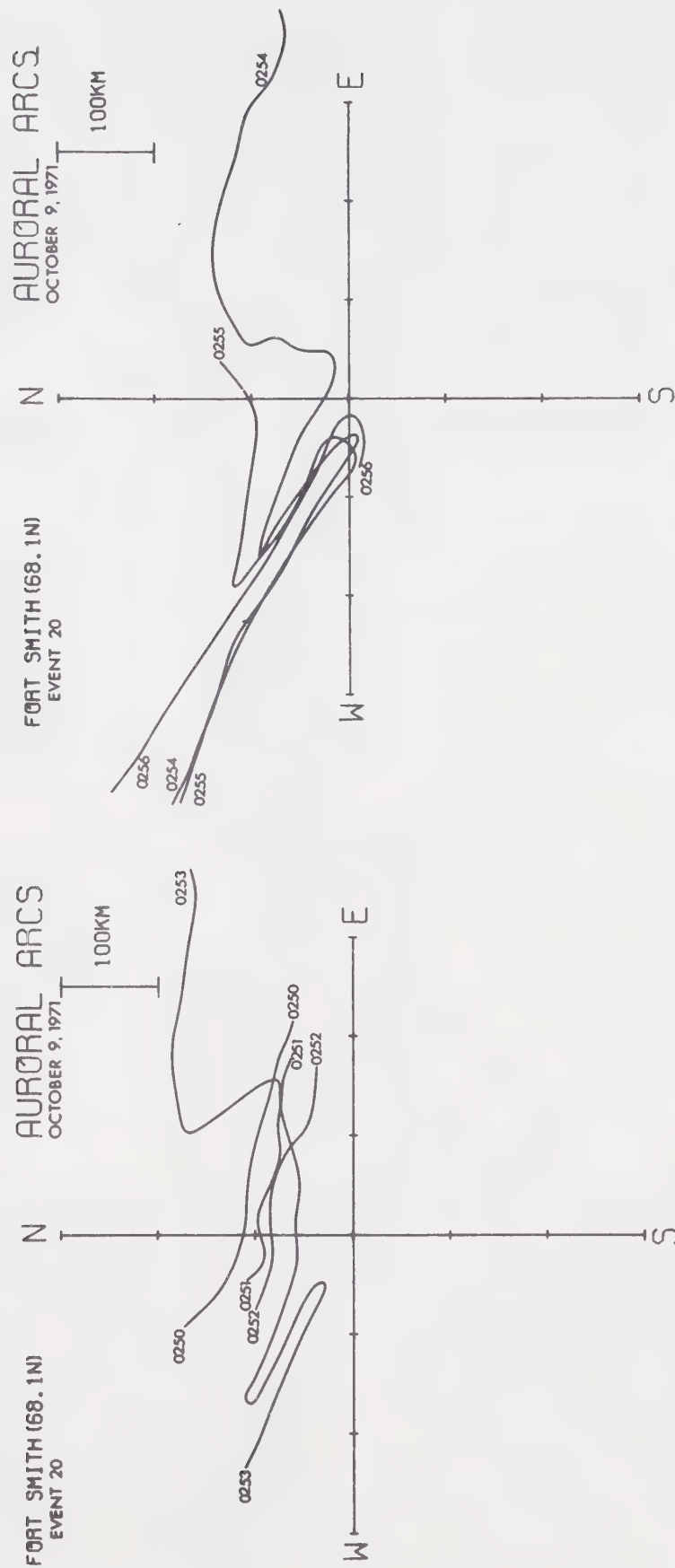
Figure 3.1b

Figure 3.1c

Figure 3.2a

AURORAL ARCS
OCTOBER 9, 1971

100KM

FORT SMITH (68.1N)
EVENT 22

N

E

S

M

0307
0308
0309
0310
0311
0312
0313
0314
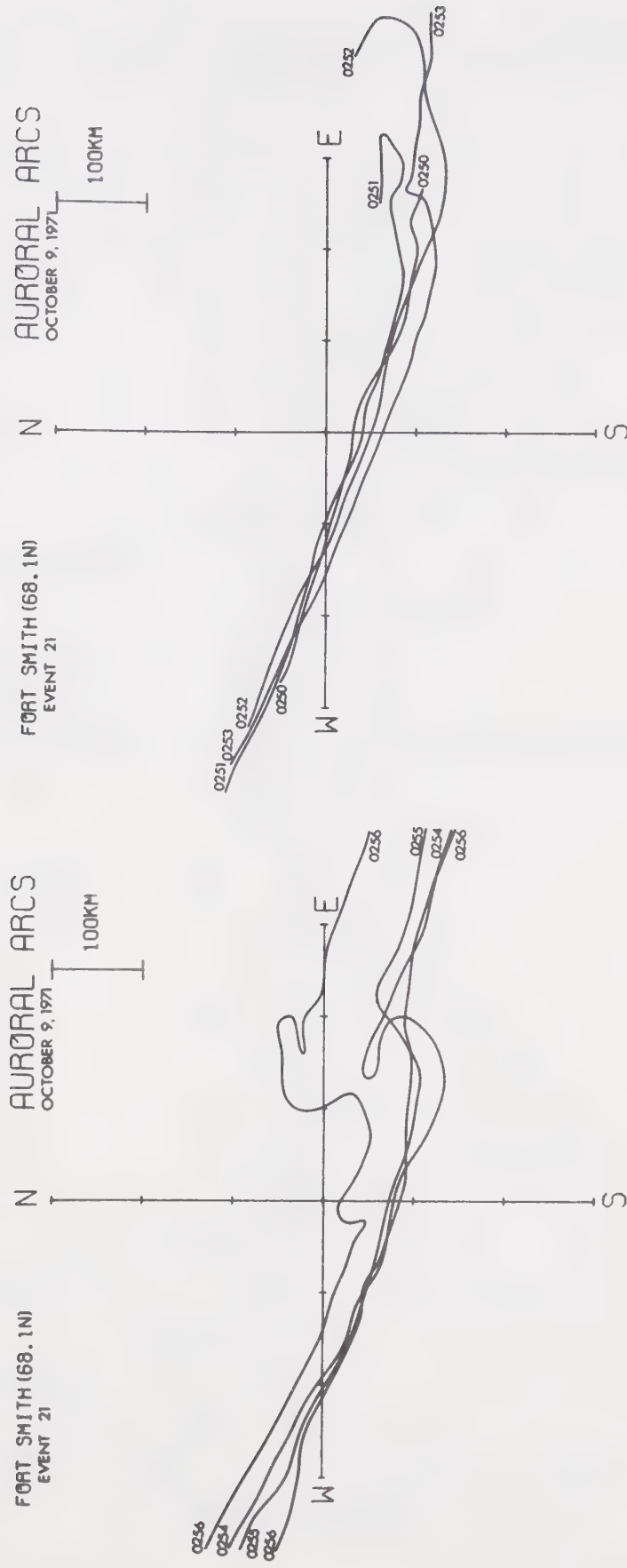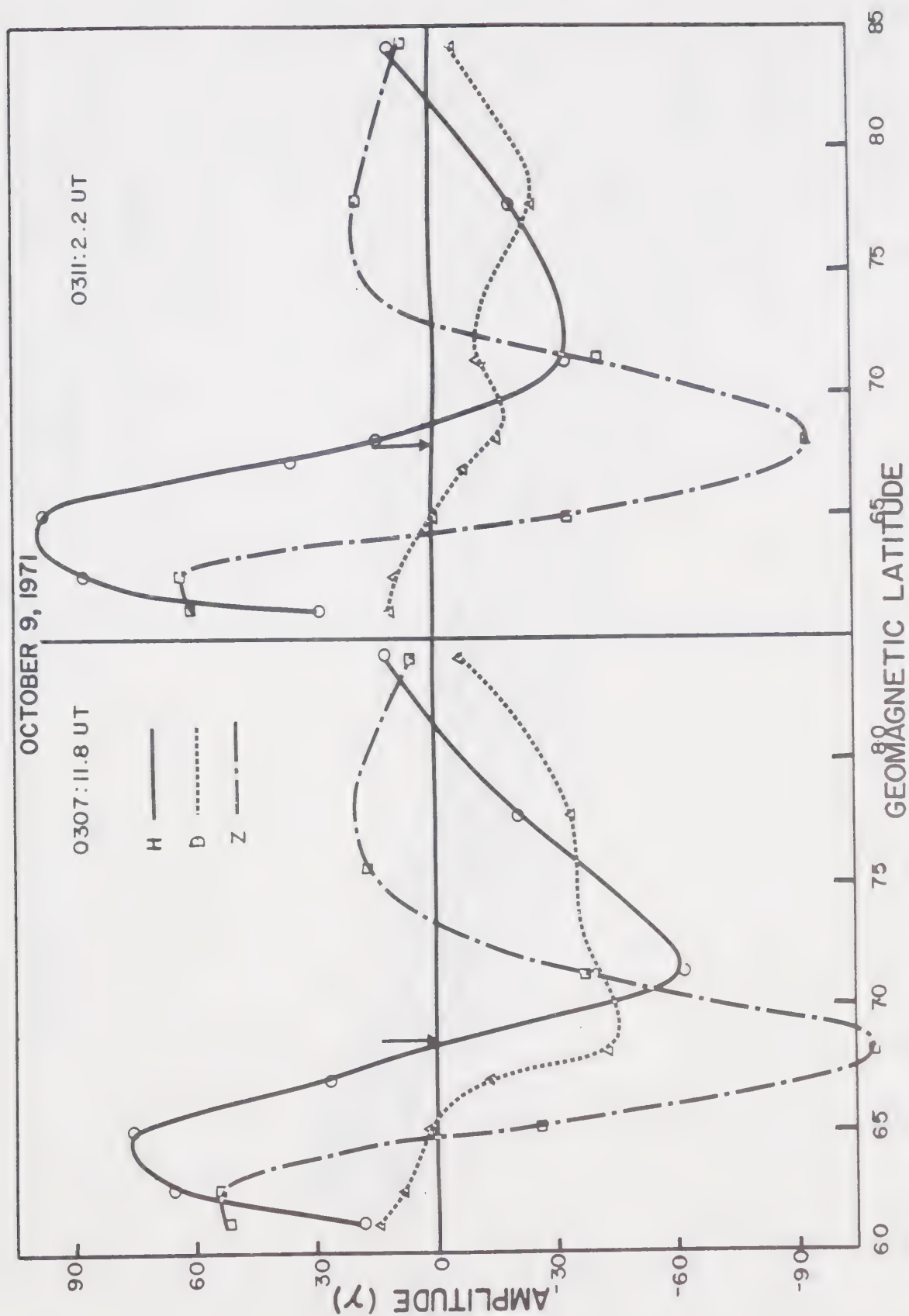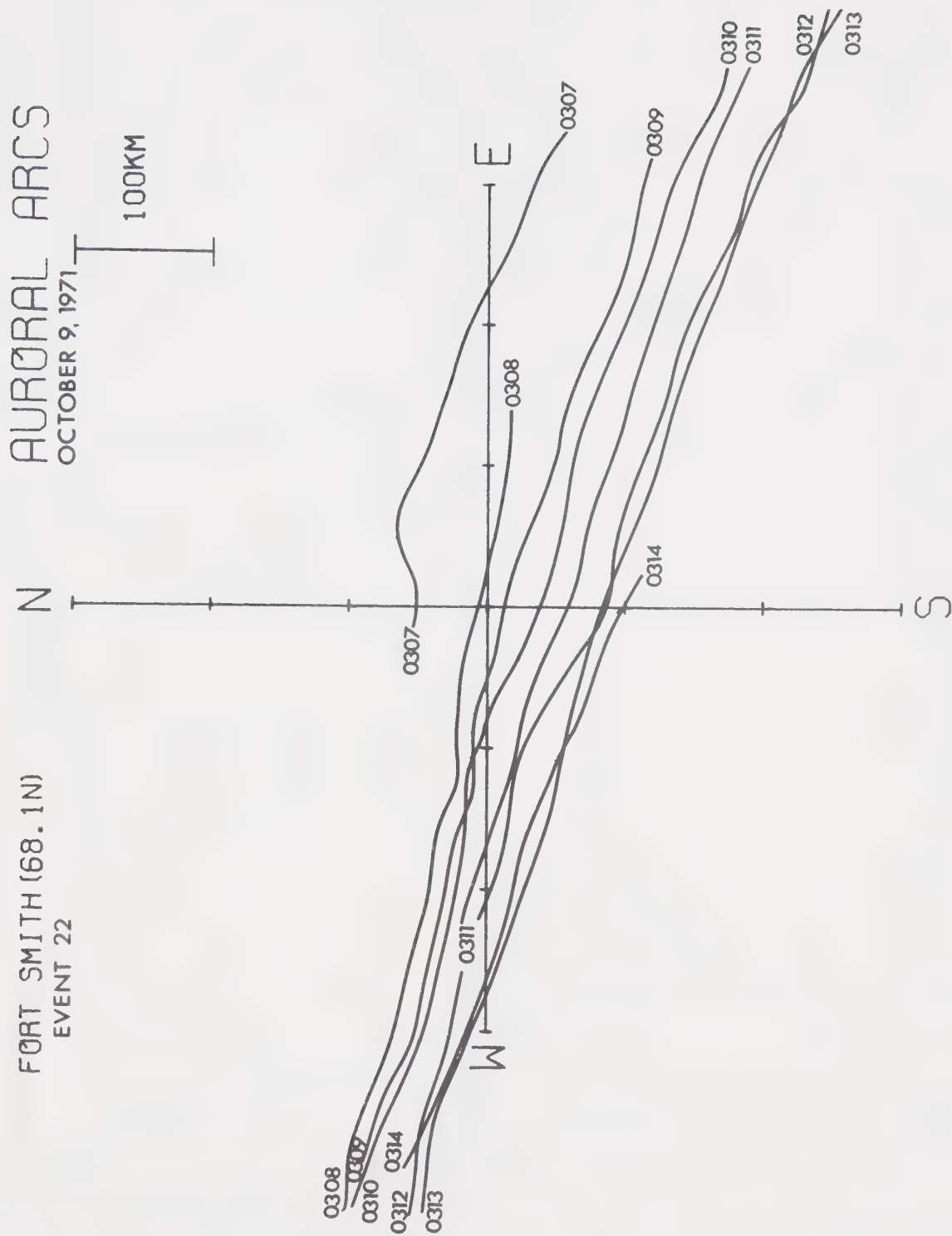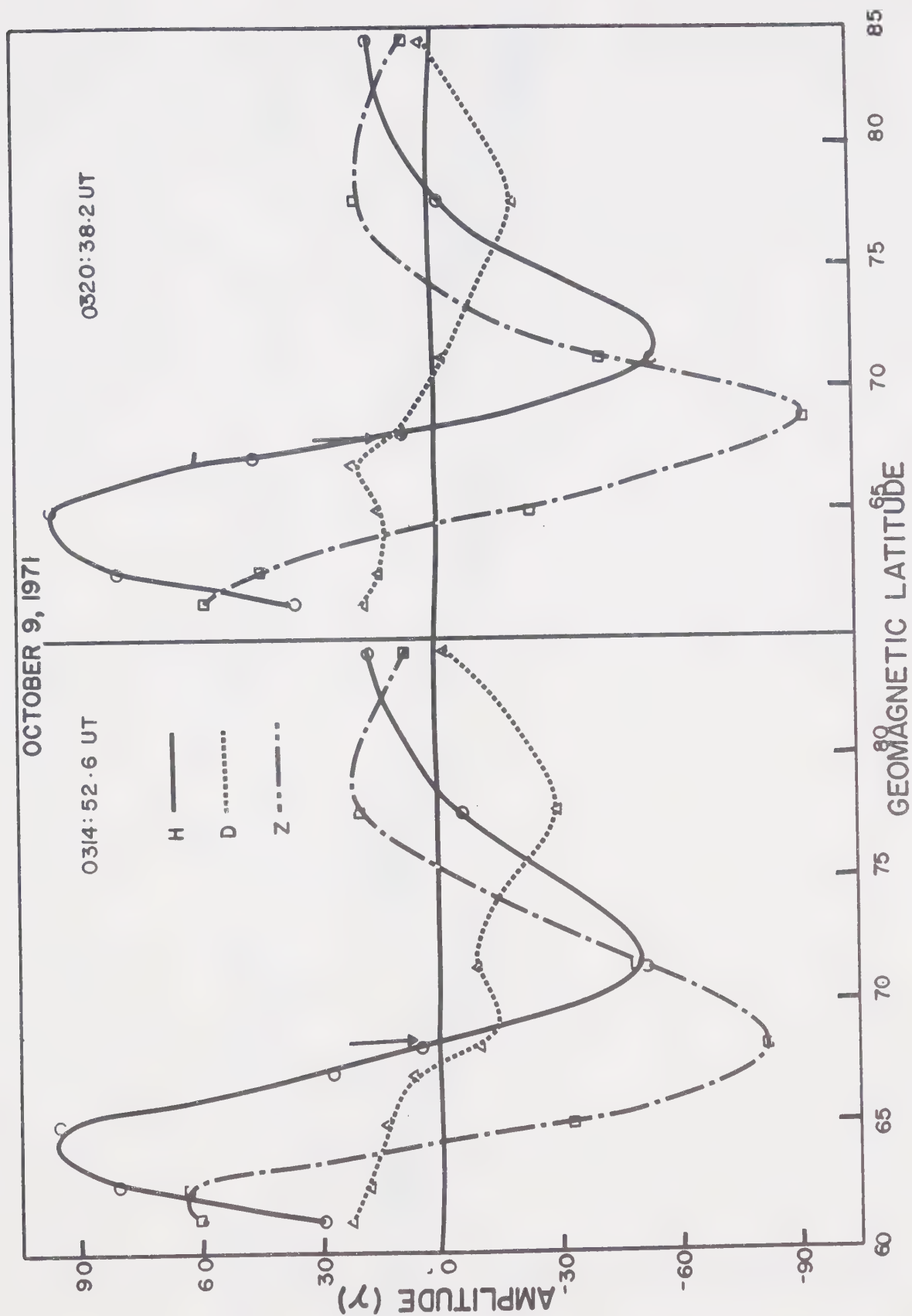
Figure 3.2b
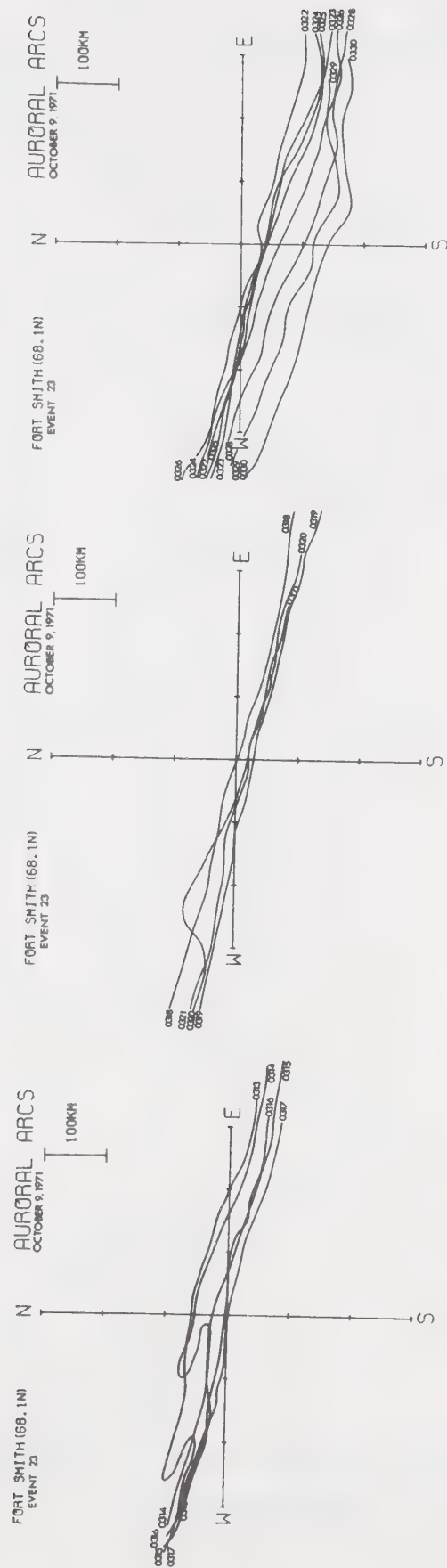
Figure 3.3a

Figure 3.3b
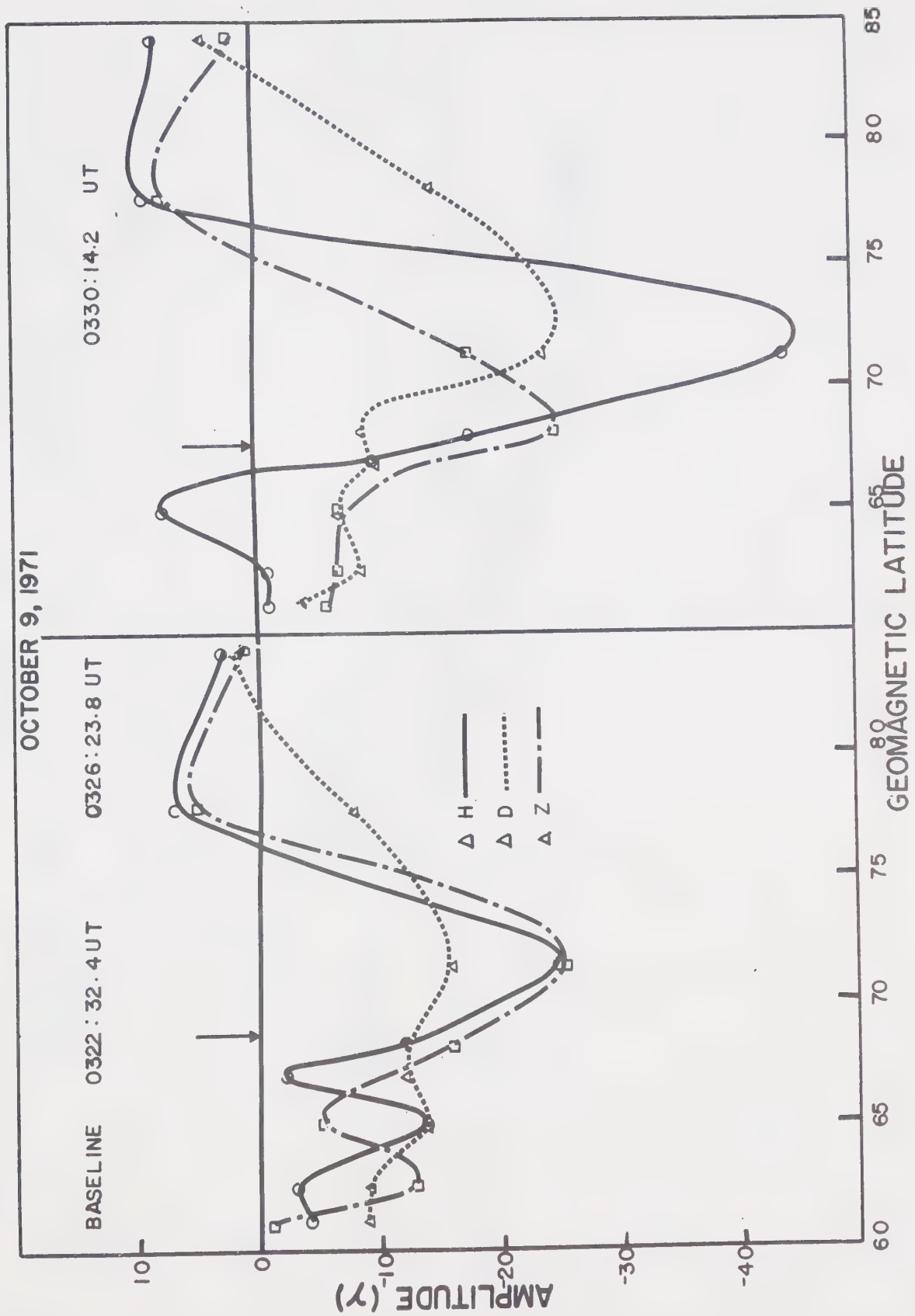
Figure 3.4a
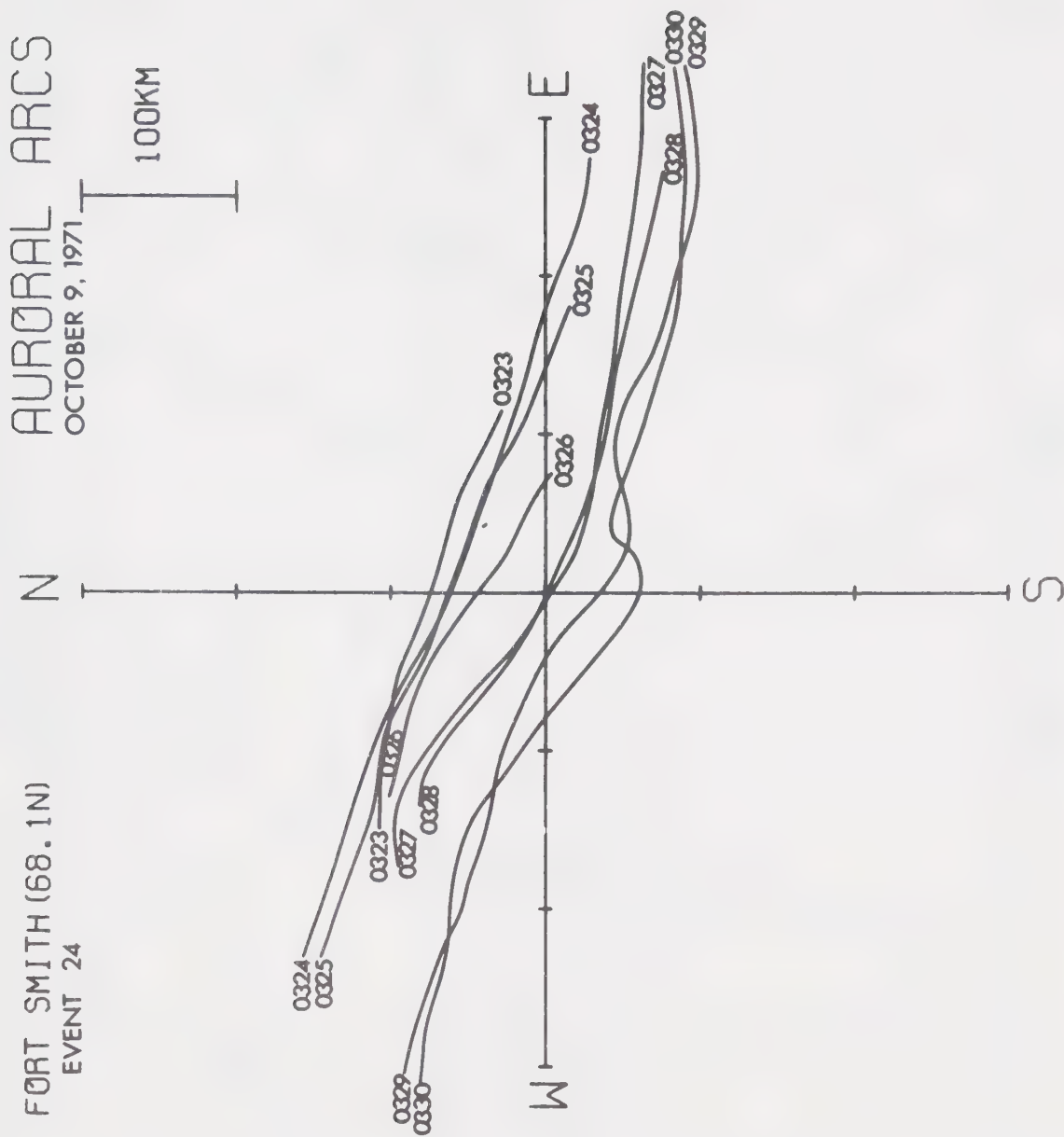
Figure 3.4b

Figure 3.5a

45

Figure 3.5b

46
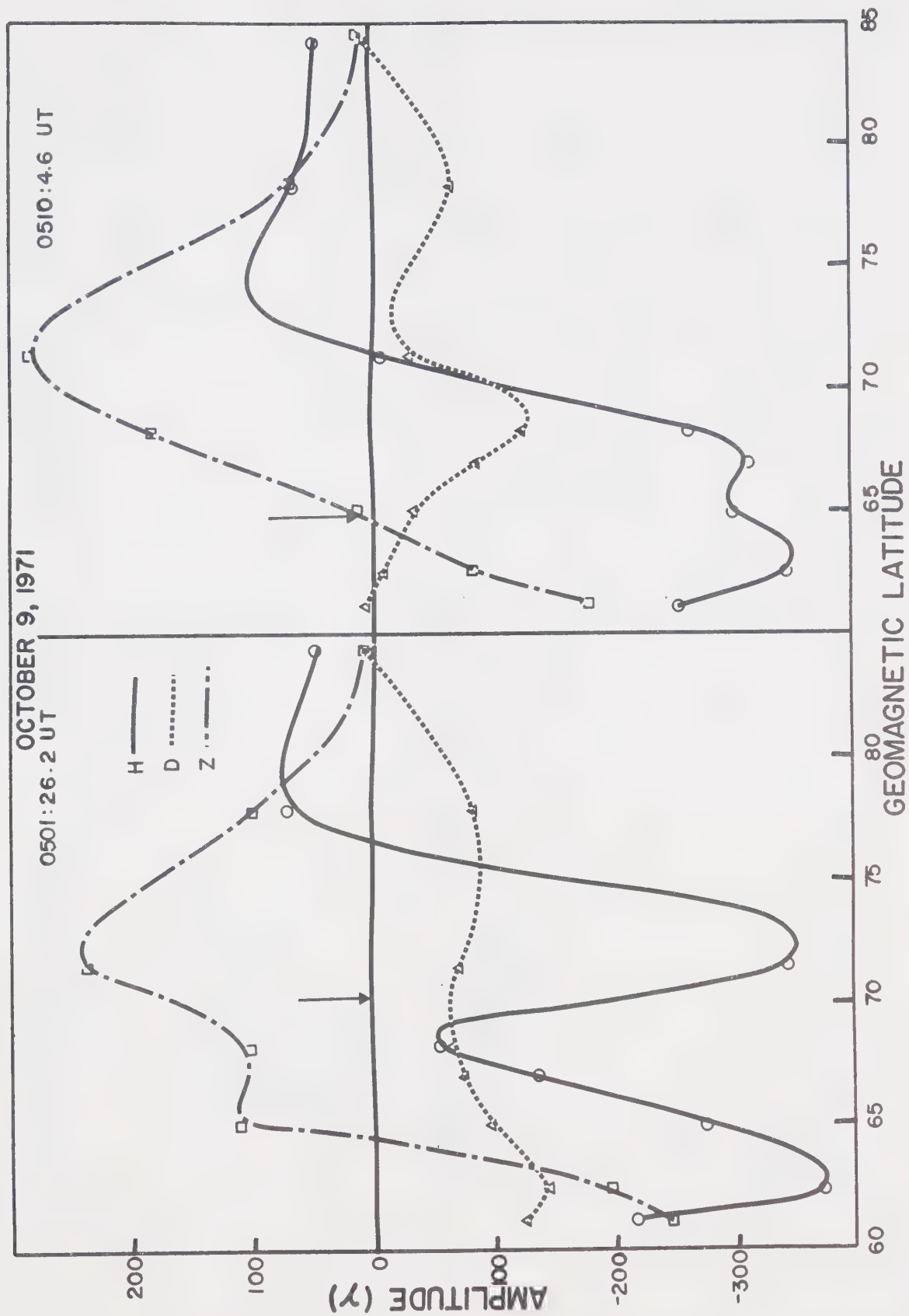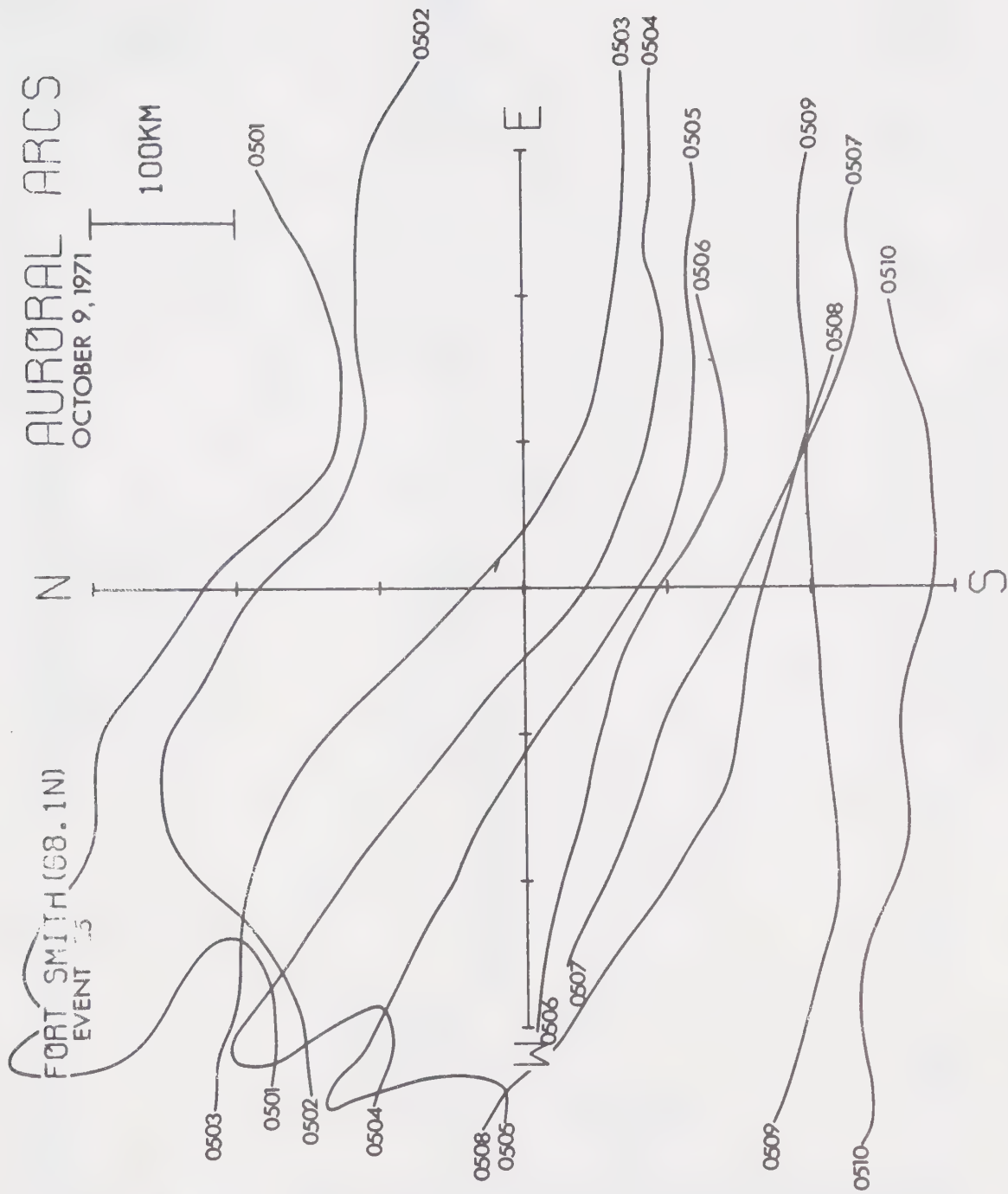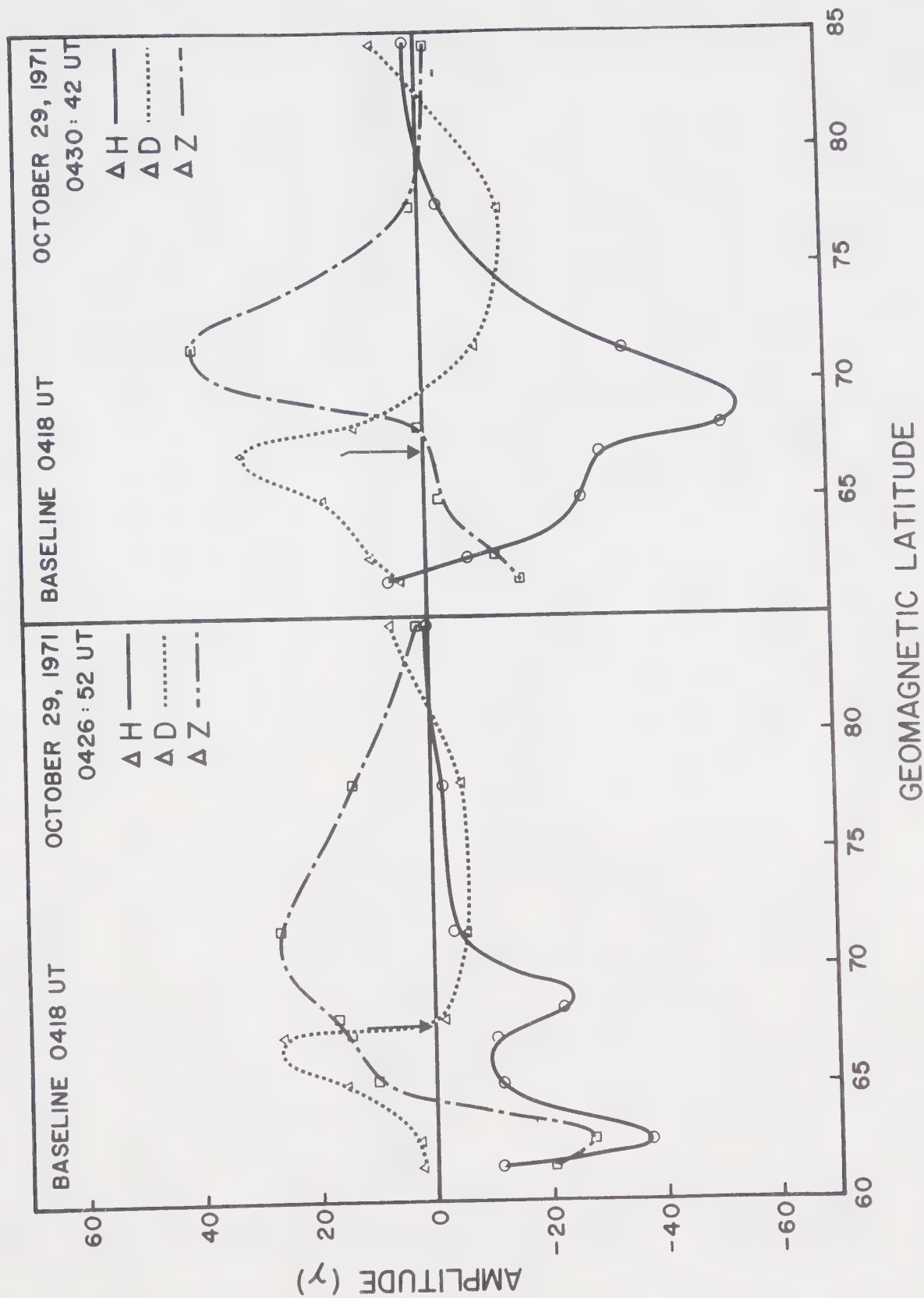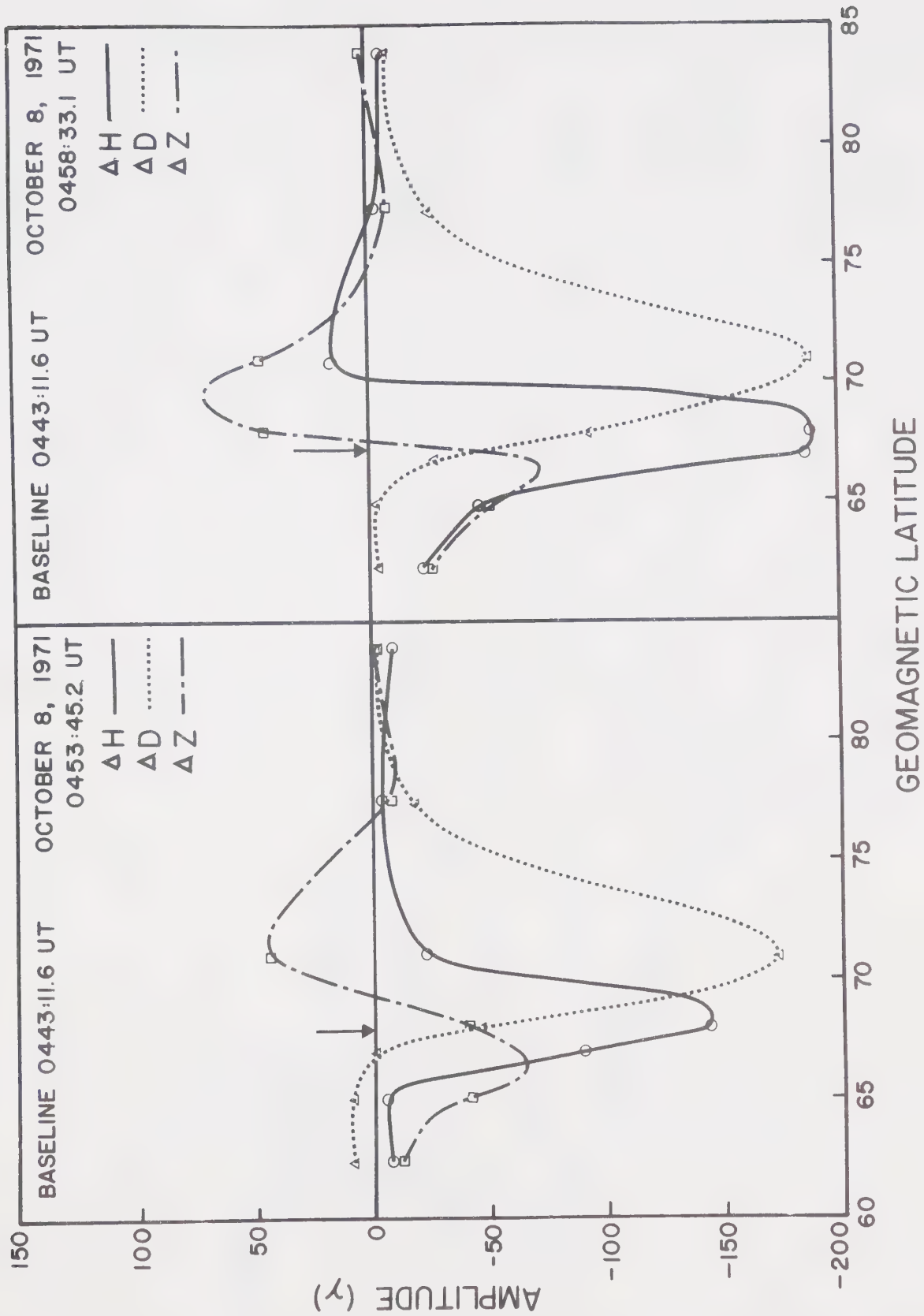
Figure 3.6

Figure 3.7a

AURORAL ARCS

FORT SMITH (68.1N)
OCTOBER 8, 1971

100KM

N

W   E   S

0451
0450
0451
0452
0453
0454
0455

0452
0453
0454
0455
0456

0456
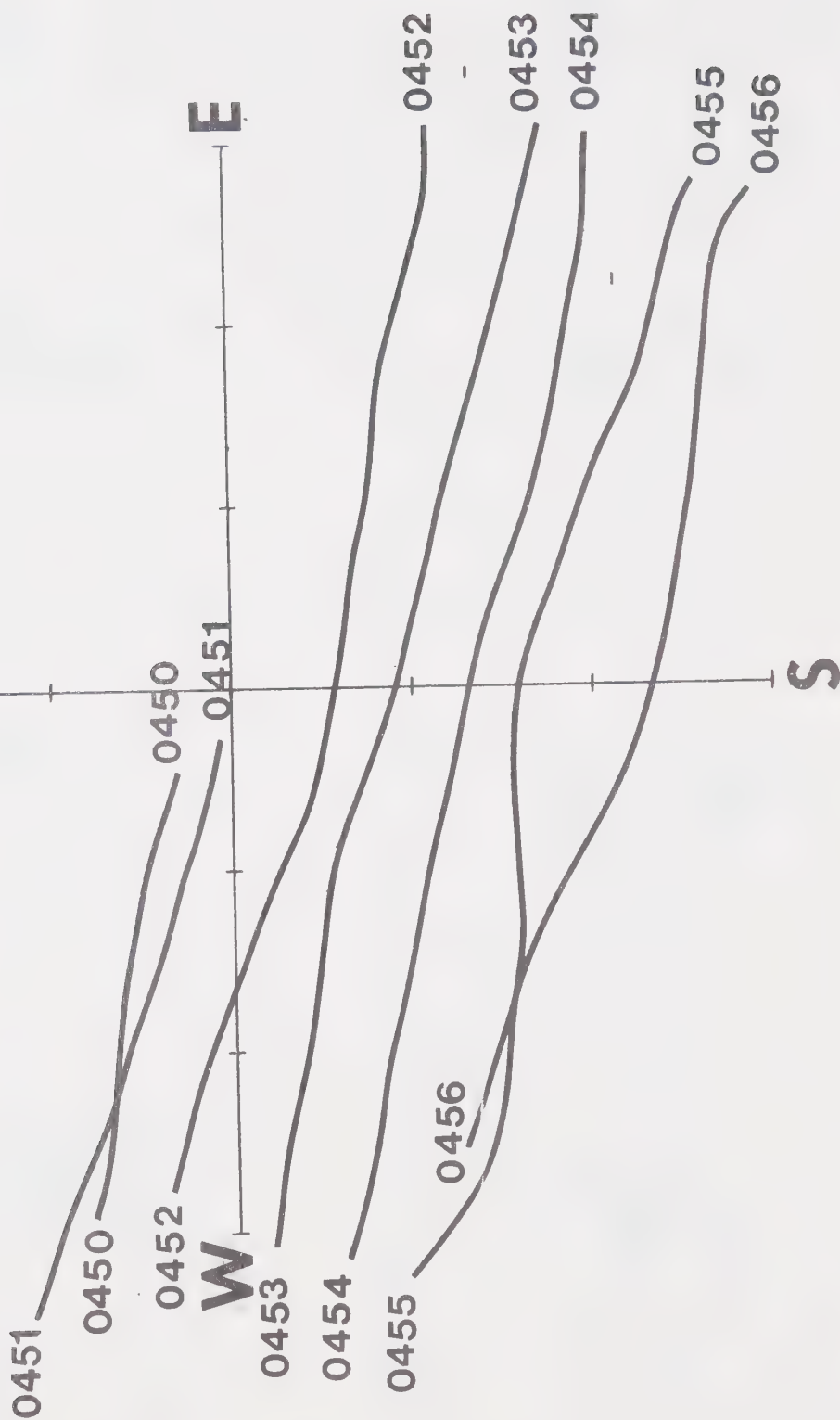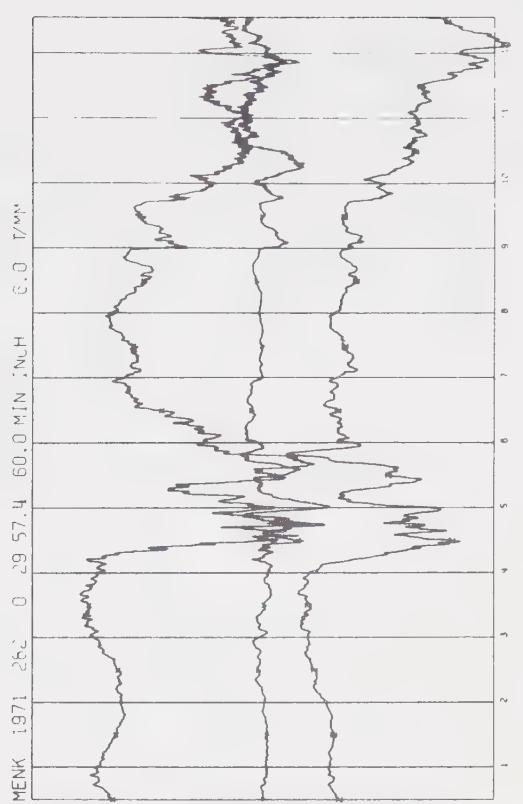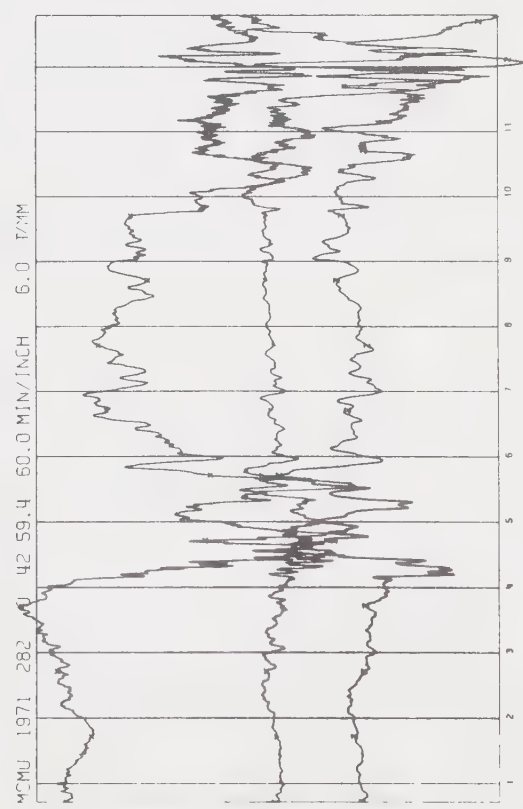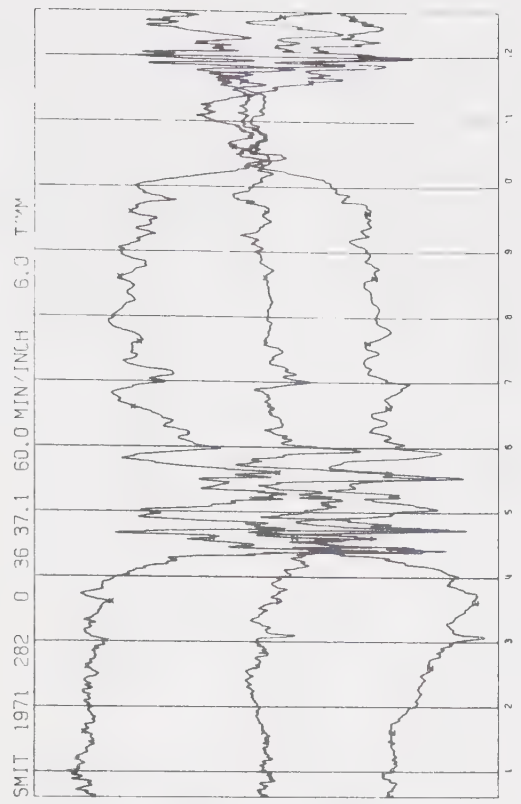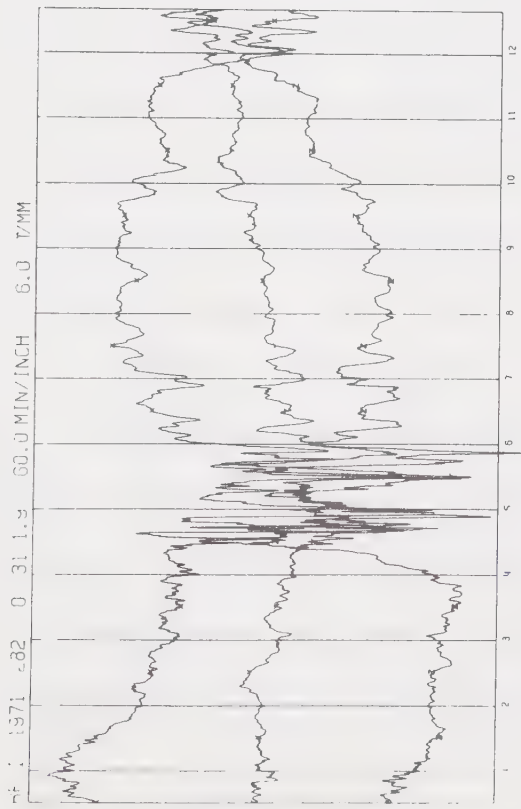
Figure 3.7b

Figure 3.8

Event 25 (October 9, 1971, 0501-0510 UT) presents a different situation. Here we have a very clear double westward current system, which decays during the course of the event. The arcs are associated with the more northward one of the two current systems (see Figure 3.5). The boundary between the two current systems, as much as it is possible to identify one, appears to move southward with the arcs during the event.

Event 37 (October 29, 1971, 0420-0430 UT) is also associated with a double current system (Figure 3.6). However, it is more complicated than event 25, in that both systems involved here are of approximately equal strength, resulting in a very greatly distorted profile. We note that this double current system also decays by the end of the event. We can identify a general southward motion of the current system as the arcs drift south, but the distortion makes it impossible to determine anything more definite.

Not all events were as complex as the foregoing. As an example, we have event 19 (October 8, 1971, 0450-0456 UT) (Figure 3.7) for which the latitude profile behaves in the standard manner, except for the extremely large negative ΔD regime poleward of the electrojet. As mentioned, this is indicative of enhanced polar cap

convection. In this case, the very large negative ΔD is associated with an ionospheric electric field of 26 mV/m, which is a good deal higher than the average value of 16 mV/m.

4. DISCUSSION AND CONCLUSIONS

4.1 Mozer's Model

Mozer (1971) has proposed a model of magnetospheric
substorms based on the behaviour of magnetospheric
electric fields during substorms. Briefly, this model
states that a westward electric field is created in the
magnetotail due to the connection of interplanetary mag-
netic field lines with the Earth's dipole field lines at
the magnetopause during periods when the interplanetary
magnetic field has a southward pointing component. This
electric field, which appears approximately an hour
before the onset of the substorm, is then responsible
for the inward convection of plasma in the magnetotail.
The speed of this convection is given by E/B (as has been
shown here). Since the electric field is constant to
within a factor of 2 over the range L = 4 to L = 9 (Mozer
and Manka, 1971), the speed of inward convection is
inversely proportional to the strength of the magnetic
field. This inverse dependence results in a build-up of
plasma at locations of strongest magnetic field strength,
namely, around the local midnight sector deep in the
magnetosphere. After a sufficient time, the pressure
gradients which result from this build-up of plasma
initiate a plasma instability, and the plasma is

precipitated. The auroral arcs that are generated from this particle precipitation then drift equatorward. Thus, this model predicts the occurrence of equatorward drifting auroral arcs prior to the onset of a magnetic substorm, that is, during the growth phase of a substorm. It is clear that this prediction is a direct consequence of the fact that the westward electric field is present approximately an hour before the substorm, and the assumption that precipitation results from the instabilities caused by the plasma pressure gradients.

4.2   The Kennel-Petschek Mechanism

Brice (1970) has suggested that an injection of cold plasma into the magnetosphere could result in the sudden subjection of keV particles to the stable trapping limit proposed by Kennel and Petschek (1966).

The Kennel-Petschek theory is based on the fact that the precipitation of energetic electrons into the ionosphere is apparently a result of first adiabatic invariant violation. Such a violation requires time variations in the magnetic field of the order of the electron cyclotron frequency; it therefore appears that high-frequency fluctuations in the whistler mode are the most probable cause of the violation of the first adiabatic invariant. The injection of the cold plasma enhances

the whistler mode turbulence. It has been observed that the whistler mode is unstable for a sufficiently aniso-tropic pitch angle distribution (Cornwall, 1965). Hence, if an anisotropic pitch angle distribution is maintained, wave energy can be generated in the magnetosphere.

The stability of the wave growth depends primarily on particles in cyclotron resonance. In a spatially finite plasma, to maintain a self-sustaining pitch angle diffusion, both escaping particles and waves must be replaced. We see that the number of resonant particles must then adjust by balancing the acceleration and pre-cipitation of particles to ensure that the wave growth rate exactly replaces the escaping wave energy. Clearly, a growth rate that is too large will create an accumulation of wave energy, which enhances particle precipitation; this, in turn, reduces the growth rate to the value neces-sary to maintain a steady-state distribution of the waves. Therefore, there is an upper limit to the stably trapped particle flux. However, the characteristic energy for cyclotron interactions is the magnetic energy per parti-cle; hence this limit applies only to particles whose energy is greater than a threshold energy E_T , given by

$$E_T \propto \frac{B^2}{2\mu_0 N}$$

where B is the magnetic field strength, μ_0 is the

permeability of free space, and N is the ambient particle
number density.

Hence, an injection of cold plasma into a volume of
energetic plasma would decrease the threshold energy E_T
to a lower value E_T'. This results in a larger number of
particles, having energies greater than the new threshold
energy E_T'; thus a greater energy range of particles are
brought under the conditions for the stable trapping limit.

4.3 Proposed Mechanism of Auroral Particle Precipitation

Vasyliunas (1968) and Frank (1968) have shown that
the plasma sheet has a sharp and well-defined inner edge
in the nightside magnetosphere, which moves inwards during
periods of substorm activity. This boundary is comprised
of a region of low energy electrons, whose number density
is the same as that observed in the interior of the plasma
sheet. Siscoe and Cummings (1969) have suggested that
the inward motion of the inner edge of the plasma sheet
occurs prior to the substorm. In their theory, there is
a balance between the force exerted on the magnetotail
by the solar wind, and the force between the Earth and
the magnetotail. The tangential stress between the mag-
netotail and the solar wind is responsible for moving

magnetic flux into the tail. The magnetic flux is stored
in the tail and returns to the magnetosphere at lower
latitudes, but at a slower rate than the rate at which it
is stored (Axford, 1965). As the tail flux increases,
the normal pressure on the tail remains almost constant,
and is balanced by the force on the tail from the solar
wind. To accommodate the increase in flux, the radius
of the tail increases, and the inner edge of the plasma
sheet moves Earthward. This inward motion occurs during
the build-up process in the tail, that is, prior to the
onset of the substorm. The inward motion is stopped when
the tangential stress on the tail is not balanced by the
force on the Earth. At this stage the substorm is initia-
ted and the plasma sheet reestablishes itself back in the
magnetotail. The process repeats itself at the end of the
substorm, if the driving force on the tail is still active.

The inward motion of the inner edge of the plasma
sheet is accompanied by a thinning of the plasma sheet
(Hones et al, 1967) and a build-up of the asymmetric ring
current in the evening sector (Cummings et al, 1968).
It has been proposed by Atkinson (1970) that the inward
convecting plasma will be precipitated into the auroral
zone ionosphere through the Kennel-Petschek mechanism of
pitch angle scattering.

We now propose a model for the generation of equatorward drifting auroral arcs, based on the theoretical and observational material presented in this and the previous sections. During the pre-substorm period, the energetic electron population (E > 1 kev) would be so low as to be below the threshold level necessary for violation of the stable trapping limit even were the threshold energy E_T to be attained. Thus the inward motion of the plasma sheet would not be associated with precipitation of energetic electrons, and thus no equatorward drifting arcs would be observed. During the expansive phase of the substorm, an azimuthally confined sector of auroral arcs would expand poleward creating a distorted region known as the auroral bulge (Akasofu, 1964). Only an azimuthally confined portion of the plasma sheet which maps into the auroral bulge will be distorted such that its Earthward edge will be forced back into the tail. There is considerable evidence that substorms occur in confined azimuthal sectors as observed both in the magnetotail and at the Earth's surface (Rostoker and Camidge, 1971). Thus it should be clear that the inner edge of the plasma sheet will be further from the Earth in the substorm-distorted region than on either side of it.

During the period of the expansive phase after the arcs have reached their most poleward direction, the

bright auroral arcs are confined to the northern border
of the auroral oval. This northern border is quite
latitudinally confined and therefore maps into a rather
limited range of L shells. It is on this limited range
of the shells that the population of auroral electrons is
energized. During the final stages of the expansive
phase, the plasma sheet particles will gradient drift
into the region of the magnetosphere which maps into the
auroral bulge region in the ionosphere.

When the decay phase starts, the energetic electrons
at the northern border of the oval are $\underset{\sim}{E} \times \underset{\sim}{B}$ drifted Earth-
ward (under the action of the tail electric field) into
the warm plasma sheet particles which have gradient drifted
in equatorward of the L-shell populated by the energetic
electrons. This warm plasma has densities of 0.4-25 cm^{-3}
(Vasyliunas, 1968), and this may easily cause the charac-
teristic energy E_T to drop to encompass the auroral electron
energy range of 1-10 keV. The enveloping of the hot plasma
(from the L-shell) in the relatively cooler plasma in the
ring current has the same effect as that proposed by Brice
(1970). The Kennel-Petschek stable trapping limit is then
violated and precipitation results, causing the generation
of the auroral arcs. The L-shell of energetic electrons
is simultaneously convected inwards and precipitating
electrons. This results in the apparent equatorward

motion of the auroral arcs generated by the precipitation.
This view of the generating mechanism of the equatorward
drifting arcs is supported to some extent by the fact
that the average speed of inward motion of the inner edge
of the plasma sheet between 10 R_E and 6 R_E is ~12 km/sec
(Vasyliunas, 1968), which maps into the ionosphere as an
average velocity of ~530 m/sec. This value compares favo-
rably with the most probable range of drift velocities in
this study which lies between 400-600 m/sec.

From this theory, one would not expect southward
drifting arcs during the growth phase of a substorm.
When the plasma sheet moves inward prior to the substorm,
the energetic particle population in the nightside mag-
netosphere is not large enough for the stable trapping
limit to be violated. The occurrence of the substorm
results in the energization of large numbers of particles,
so that the subsequent inward motion of these energetic
particles through a region near the Earthward edge of the
plasma sheet would result in continual precipitation of
auroral particles until the auroral electron population
dropped below the stable trapping limit. Thus southward
drifting arcs would be associated with the recovery phase
of a magnetic substorm. This is confirmed by our observa-
tional findings.

In spite of the foregoing arguments, there is still
a possible case that southward drifting arcs could be

associated with the growth phase of a substorm. The
theory presented here is based on the following model
of a magnetic substorm: During the development phase
of the substorm the plasma sheet moves Earthward under
the action of the convective force in the magnetotail.
Due to the low flux of trapped energetic particles in the
nightside magnetosphere, particle precipitation is not
very likely at this stage. During the substorm activity,
some of these trapped particles are accelerated so that
their energy exceeds the threshold energy E_T and their
large flux at this time makes them subject to the stable
trapping limit. After the expansive phase of the sub-
storm, the inner edge of the plasma sheet in an azimuthally
confined region will reestablish itself further back in
the magnetotail. At this stage, that is, the recovery
phase of the substorm, the distortion of the inner edge
of the plasma sheet disappears and the energized electrons
at the edge of the auroral bulge would thus be governed
by the stable trapping limit.

However, in the magnetosphere, the inward motion
of the plasma sheet associated with the growth phase is
identical in character to the inward motion of the re-
established plasma sheet and regions of enhanced energetic
electron population associated with the recovery phase.
The second inward motion may thus conceivably be identified

as the growth phase for subsequent substorm activity; in this case the growth phase would have associated southward drifting arcs. Therefore, the apparent contradiction between our results and those of Mozer (1971) and Feldstein (1972) is due in fact to the existing ambiguity in differentiating between a growth and recovery phase of a magnetic substorm. Despite this ambiguity, it is clear that no southward drifting arcs would appear during the growth phase of an isolated substorm, or prior to the onset of a period of sustained substorm activity.

It is important to point out that the second inward motion of the plasma sheet may or may not occur, depending on the continued existence of the enhanced convection electric field. Thus we will not always have southward drifting arcs associated with the recovery phase of the substorm. Another possibility is that there is a lapse of time between the first and second inward motions of the plasma sheet. We would then still have particle precipitation during the second inward motion of the plasma sheet, since our mechanism is not time dependent, but depends only on the trapped particle flux. (It should be noted that if the "lapse of time" is of any considerable extent, the energetic trapped particle population is likely to move out of the potential precipitating zone, due to the gradient drift of the electrons).

4.4 Conclusions

Assuming the validity of the theory of particle pre-
cipitation presented here, it is at once clear that the
velocity of southward drift of the arcs is directly
related to the value of the ionospheric electric field;
the electric field value may then be inferred from the
drift velocity of the arcs (Kelley et al, 1971). The
validity of this relationship is shown by the agreement
of the electric field values obtained in this manner, with
the values obtained by other methods, such as balloon
measurements (Mozer and Manka, 1971), barium cloud tech-
niques (Haerendel and Lüst, 1970), and whistler techniques
(Carpenter et al, 1972).

The evidence of the magnetic records associated
with the auroral events showed that during a sample time
of fifteen months and over a total of 43 events of south-
ward drifting arcs, there was not one instance where south-
ward drifting arcs were associated with the growth phase
of the associated polar magnetic substorm. This is
consistent with the view that there are not large fluxes
of trapped energetic particles in the outer region of the
nightside quiet-time magnetosphere. Hence, the immersion
of regions populated by auroral electrons in the plasma
sheet will not produce precipitation of those energetic
electrons if their population is below the stable trapping

limit. Only after substorm activity has resulted in the acceleration of large numbers of energetic electrons, would their population be large enough to be stimulated by the Kennel-Petschek mechanism causing particle precipitation and the generation of auroral arcs. The fact that 34 of the 43 events were associated with the recovery phase of a substorm, and none with the development phase, shows that the appearance of southward drifting arcs is an invalid auroral signature for the growth phase of a magnetic substorm, unless one considers that the growth phase and recovery phase may coexist after a period of earlier substorm activity.

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TABLE A1 : LIST OF EVENTS

Times for all events are given in UT (LT+7). The
linear mapping is accurate to 250 km to the north and
south of the zenith. For convenience of notation, the
northern direction has been arbitrarily designated
positive along the longitudinal axis, and the southern
direction negative. The origin of the co-ordinate
system is the zenith. Thus an arc whose location is
-100 km with a velocity of -400 m/sec is 100 km south
of the zenith and travelling southward with a speed of
400 m/sec.

<u>List of Events</u>

Event 1 : July 28, 1970 (Day 209)

Time(UT)	Location (km)	Velocity (m/sec)
0834	146	
0835	138	-133
0836	134	- 66.7
0837	119	-250

$$\bar{v}_1 = -149.9 \ \text{m/sec.}$$

Event 2 : July 28, 1970 (Day 209)

Time (UT)	Location (km)	Velocity (m/sec)
0839	138	
0840	125	-217
0841	113	-200

$$\bar{v}_2 = -208.5 \ \ \text{m/sec}.$$

Event 3 : September 22, 1970 (Day 265)

Time (UT)	Location (km)	Velocity (m/sec)
1047	-69	
1048	-67	33.3
1049	-75	-300
1050	-91	-267
1051	-94	- 50
1052	-105	-183
1053	-110	- 83
1054	-120	-167
1055	-135	-250
1056	-140	- 83

$$\bar{v}_3 = -165.4 \ \ \text{m/sec}.$$

Event 4 : October 12, 1970 (Day 285)

Time (UT)	Location (km)	Velocity (m/sec)
0427	− 28	
0428	− 44	−267
0429	− 94	−833
0430	−105	−183

$$\bar{v}_4 = -506.6 \ \ m/sec.$$

Event 5 : October 12, 1970 (Day 285)

Time (UT)	Location (km)	Velocity (m/sec)
0711	− 88	
0712	− 81	117
0713	− 94	−217
0714	−110	−267
0715	− 47	1050

$$\bar{v}_5 = -242 \ \ m/sec.$$

Event 6 : October 15, 1970 (Day 288)

Time (UT)	Location (km)	Velocity (m/sec)
0802	− 97	
0803	−110	−217
0804	−115	− 83
0805	−115	0

$$\bar{v}_6 = -150 \ \ m/sec.$$

Event 7 : October 15, 1970 (Day 288)

Time (UT)	Location (km)	Velocity (m/sec)
0943	-19	
0944	-50	-517
0945	-81	-517
0946	-68	217
0947	-97	-483

$$\bar{v}_7 = -505.7 \quad m/sec.$$

Event 8 : October 24, 1970 (Day 297)

Time (UT)	Location (km)	Velocity (m/sec)
0605	69	
0606	53	-267
0607	25	-467
0608	-10	-587
0609	-20	-167
0610	-50	-500

$$\bar{v}_8 = -397.6 \quad m/sec.$$

Event 9 : October 25, 1970 (Day 298)

Time (UT)	Location (km)	Velocity (m/sec)
0729	-110	
0730	-190	-1333
0731	-215	- 417
0732	-220	- 83
0733	-120	1667

$$\bar{v}_9 = -611.0 \quad m/sec.$$

Event 10 : October 25, 1970 (Day 298)

Time (UT)	Location (km)	Velocity (m/sec)
0740	141	
0741	100	-683
0742	69	-517
0743	50	-317

$$\bar{v}_{10} = -505.7 \ \text{m/sec}.$$

Event 11 : November 3, 1970 (Day 307)

Time (UT)	Location (km)	Velocity (m/sec)
0745	184	
0746	175	-150
0747	159	-267

$$\bar{v}_{11} = -208.5 \ \text{m/sec}.$$

Event 12 : November 5, 1970 (Day 309)

Time (UT)	Location (km)	Velocity (m/sec)
0838	172	
0839	281	1817
0840	141	-2333
0841	103	- 633
0842	91	- 200

$$\bar{v}_{12} = -1022.0 \ \text{m/sec}.$$

Event 13 : February 23, 1971 (Day 54)

Time (UT)	Location (km)	Velocity (m/sec)
0650	− 40	
0651	− 60	− 333.3
0652	− 79	− 316.7
0653	−102	− 383.3
0654	−102	0.0
0655	−130	− 466.7
0656	−221	−1516.7

$$\bar{v}_{13} = -502.8 \ \text{m/sec.}$$

Event 14 : October 8, 1971 (Day 281)

Time (UT)	Location (km)	Velocity (m/sec)
0331	257	
0332	220	− 616.7
0333	193	− 450.0
0334	115	−1300.0
0335	114	− 16.7
0336	91	− 383.3
0337	60	− 516.7
0338	27	− 550.0
0339	20	− 116.7
0340	−20	− 666.7

$$\bar{v}_{14} = -513.0 \ \text{m/sec.}$$

Event 15 : October 8, 1971 (Day 281)

Time (UT)	Location (km)	Velocity (m/sec)
0346	220	
0347	149	-1183.3
0348	145	- 66.7
0349	121	- 400.0
0350	120	- 16.7
0351	100	- 333.3
0352	60	- 666.7
0353	27	- 550.0
0354	10	- 283.3

$$\bar{v}_{15} = -437.5 \quad m/sec.$$

Event 16 : October 8, 1971 (Day 281)

Time (UT)	Location (km)	Velocity (m/sec)
0350	218	
0351	188	- 500.0
0352	160	- 466.7
0353	147	- 216.7
0354	181	566.7

$$\bar{v}_{16} = -394.5 \quad m/sec.$$

Event 17 : October 8, 1971 (Day 281)

Time (UT)	Location (km)	Velocity (m/sec)
0445	242	
0446	236	-100.0
0447	195	-683.3
0448	175	-333.3
0449	142	-550.0
0450	110	-533.3
0451	101	-150.0
0452	80	-350.0
0453	70	-166.7
0454	70	0.0
0455	49	-350.0

$$\bar{v}_{17} = -321.7 \quad m/sec.$$

Event 18 : October 8, 1971 (Day 281)

Time (UT)	Location (km)	Velocity (m/sec)
0450	50	
0451	49	- 16.7
0452	0	-816.7
0453	0	0.0
0454	0	0.0
0455	- 1	- 16.7
0456	0	16.7
0457	-20	-333.3
0458	-38	-300.0

Event 18 : October 8, 1971 (Day 281) - continued

Time (UT)	Location (km)	Velocity (m/sec)
0459	- 51	- 216.7
0500	-130	-1316.7

$$\bar{v}_{18} = -335.2 \ \text{m/sec.}$$

Event 19 : October 8, 1971 (Day 281)

Time (UT)	Location (km)	Velocity (m/sec)
0450	32	
0451	5	- 450.0
0452	- 57	-1033.3
0453	- 90	- 550.0
0454	-132	- 700.0
0455	-159	- 450.0
0456	-231	-1200.0

$$\bar{v}_{19} = -730.6 \ \text{m/sec.}$$

Event 20 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0250	110	
0251	94	- 266.7
0252	81	- 116.7
0253	59	- 366.7
0254	28	- 516.7
0255	100	1200.0
0256	-10	-1833.3

$$\bar{v}_{20} = -620.0 \ \text{m/sec.}$$

Event 21 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0250	−28	
0251	−38	−166.7
0252	−50	−200.0
0253	−60	−166.7
0254	−78	−300.0
0255	−71	166.7
0256	−83	−200.0

$$\bar{v}_{21} = -206.7 \ \text{m/sec.}$$

Event 22 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0307	58	
0308	10	−800.0
0309	− 7	−283.3
0310	−38	−516.7
0311	−58	−333.3
0312	−89	−516.7
0313	−80	150.0
0314	−99	−316.7

$$\bar{v}_{22} = -461.1 \ \text{m/sec.}$$

Event 23 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0313	59	
0314	51	-133.3
0315	30	-350.0
0316	- 2	-533.3
0317	- 2	0.0
0318	- 2	0.0
0319	-28	-433.3
0320	-19	150.0
0321	-20	- 16.7
0322	-31	-183.3
0323	-41	-166.7
0324	-41	0.0
0325	-40	16.7
0326	-60	-333.3
0327	—	—
0328	-99	-325.0
0329	-112	-216.7
0330	-140	-466.7

$$\bar{v}_{23} = -225.6 \ \text{m/sec.}$$

Event 24 : October 9, 1972 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0323	77	
0324	62	-250.0
0325	54	-133.3
0326	44	-166.7
0327	- 4	-800.0
0328	0	66.7
0329	-38	-633.3
0330	-60	-360.7

$$\bar{v}_{24} = -391.7 \text{ m/sec.}$$

Event 25 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0501	221	
0502	189	- 533.3
0503	38	-2516.7
0504	-40	-1300.0
0505	-79	- 650.0
0506	-90	- 183.3
0507	-145	- 916.7
0508	-163	- 300.0
0509	-200	- 616.7
0510	-280	-1333.3

$$\bar{v}_{25} = -927.8 \text{ m/sec.}$$

Event 26 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0652	228	
0653	140	-1466.7
0654	123	- 283.3
0655	99	- 400.0
0656	52	- 783.3
0657	- 2	- 900.0
0658	-60	- 966.7
0659	-120	-1000.0
0700	-210	-1500.0
0701	-150	1000.0
0702	-198	- 800.0

$$\bar{v}_{26} = -900 \ \text{m/sec.}$$

Event 27 : October 9, 1972 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0700	194	
0701	170	- 400.0
0702	139	- 516.7
0703	90	- 816.7
0704	44	- 766.7
0705	20	- 400.0
0706	8	- 200.0

$$\bar{v}_{27} = -516.7 \ \text{m/sec.}$$

Event 28 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0837	132	
0838	91	-683.3
0839	51	-666.7
0840	38	-216.7
0841	-19	-950.0
0842	-25	-100.0
0843	-29	- 66.7
0844	-41	-200.0
0845	-82	-683.3
0846	-97	-250.0
0847	-108	-183.3
0848	-130	-366.7
0849	-140	-166.7
0850	-159	-316.7

$$\bar{v}_{28} = -373.1 \ \text{m/sec.}$$

Event 29 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0901	-79	
0902	-93	-233.3
0903	-118	-416.7
0904	-140	-366.7
0905	-196	-933.3

$$\bar{v}_{29} = -487.5 \ \text{m/sec.}$$

Event 30 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
0923	−39	
0924	−61	− 366.7
0925	−77	− 266.7
0926	−80	− 50.0
0927	−118	− 633.3
0928	−118	0.0
0929	−200	−1366.7
0930	−282	−1366.7

$$\bar{v}_{30} = -578.6 \text{ m/sec.}$$

Event 31 : October 9, 1971 (Day 282)

Time (UT)	Location (km)	Velocity (m/sec)
1105	14	
1106	−54	−1133.3
1107	−63	− 150.0
1108	−79	− 266.7
1109	−90	− 183.3

$$\bar{v}_{31} = -433.3 \text{ m/sec.}$$

Event 32 : October 22, 1971 (Day 295)

Time (UT)	Location (km)	Velocity (m/sec)
0724	133	
0725	117	-266.7
0726	117	0.0
0727	90	-450.0
0728	48	-700.0
0729	-11	-983.3

$$\bar{v}_{32} = -480.0 \quad \text{m/sec.}$$

Event 33 : October 24, 1971 (Day 297)

Time (UT)	Location (km)	Velocity (m/sec)
0535	180	
0536	122	-966.7
0537	91	-350.0
0538	59	-533.3
0539	40	-316.7
0540	12	-466.7
0541	-20	-533.3
0542	-60	-666.7
0543	-110	-833.3
0544	-208	-1633.3
0545	-259	-850.0

$$\bar{v}_{33} = -715.0 \quad \text{m/sec.}$$

Event 34 : October 24, 1971 (Day 297)

Time (UT)	Location (km)	Velocity (m/sec)
0538	120	
0539	92	-466.7
0540	102	166.7
0541	60	-700.0
0542	44	266.7
0543	- 2	-766.7
0544	-48	-766.7
0545	-80	-533.3

$$\bar{v}_{34} = -455.6 \quad m/sec.$$

Event 35 : October 24, 1971 (Day 297)

Time (UT)	Location (km)	Velocity (m/sec)
0842	95	
0843	70	-416.7
0844	68	- 33.3
0845	42	-433.3
0846	30	-133.3
0847	3	-450.0
0484	0	- 50.0
0849	-20	-333.3
0850	-42	-366.7
0851	-57	-250.0

$$\bar{v}_{35} = -274.1 \quad m/sec.$$

Event 36 : October 28, 1971 (Day 301)

Time (UT)	Location (km)	Velocity (m/sec)
0920	98	
0921	73	−416.7
0922	35	−633.3
0923	− 9	−733.3
0924	−49	−666.7
0925	−80	−516.7
0926	−83	− 50.0

$$\bar{v}_{36} = -502.8 \text{ m/sec.}$$

Event 37 : October 29, 1971 (Day 302)

Time (UT)	Location (km)	Velocity (m/sec)
0420	77	
0421	56	−350.0
0422	41	−250.0
0423	9	−533.3
0424	−20	−483.3
0425	−30	−166.7
0426	−30	0.0
0427	−38	−133.3
0428	−60	−366.7
0429	−69	−150.0
0430	−220	−2516.7

$$\bar{v}_{37} = -495.0 \text{ m/sec.}$$

Event 38 : October 29, 1971 (Day 302)

Time (UT)	Location (km)	Velocity (m/sec)
0429	-10	
0430	-42	-533.3
0431	-90	-800.0
0432	-93	- 50.0

$$\bar{v}_{38} = -461.1 \ \ \text{m/sec.}$$

Event 39 : October 29, 1971 (Day 302)

Time (UT)	Location (km)	Velocity (m/sec)
0434	137	
0435	111	-433.3
0436	119	133.3
0437	100	-316.7
0438	90	-166.7

$$\bar{v}_{39} = -305.6 \ \ \text{m/sec.}$$

Event 40 : October 29, 1971 (Day 302)

Time (UT)	Location (km)	Velocity (m/sec)
0438	199	
0439	162	-616.7
0440	160	- 33.3
0441	158	- 33.3
0442	139	-316.7
0443	122	-283.3

$$\bar{v}_{40} = -256.7 \ \ \text{m/sec.}$$

Event 41 : October 29, 1971 (Day 302)

Time (UT)	Location (km)	Velocity (m/sec)
0444	179	
0445	155	-400.0
0446	155	0.0
0447	117	-633.3
0448	121	66.7
0449	122	16.7
0450	112	-166.7
0451	110	-200.0
0452	100	-166.7
0453	89	-183.3
0454	59	-500.0
0455	38	-350.0
0456	21	-233.3
0457	7	-233.3
0458	-51	-966.7

$$\bar{v}_{41} = -340.3 \;\; m/sec.$$

Event 42 : October 29, 1971 (Day 302)

Time (UT)	Location (km)	Velocity (m/sec)
0456	69	
0457	47	-366.7
0458	22	-416.7
0459	19	- 50.0
0500	14	- 83.3

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Event 42 : October 29, 1971 (Day 302) - continued

Time (UT)	Location (km)	Velocity (m/sec)
0501	20	100.0
0502	-18	-633.3
0503	8	433.3
0504	4	- 66.7
0505	- 3	-116.7

$$\bar{v}_{42} = -247.6 \quad m/sec.$$

Event 43 : October 30, 1971 (Day 303)

Time (UT)	Location (km)	Velocity (m/sec)
0310	248	
0311	240	-133.3
0312	235	- 83.3
0313	239	66.7
0314	201	-633.3
0315	203	33.3
0316	183	-333.3
0317	160	-383.3
0318	131	-483.3
0319	103	-1120.0
0320	100	- 50.0
0321	71	-483.3
0322	42	-483.3
0323	10	-533.3
0324	-12	-366.7

Event 43 : October 30, 1971 (Day 303) - continued

Time (UT)	Location (km)	Velocity (m/sec)
0325	-40	-466.7
0326	-60	-333.3
0327	-60	0.0

$$\bar{v}_{43} = -392.4 \quad \text{m/sec.}$$

TABLE A2 : SUMMARY OF RESULTS

Event No.	Date of Event	Time of Event (UT:=LT+7)	Ionospheric Velocity (m/sec)	Equatorial Plane Velocity (m/sec)	Equatorial Plane Electric Field (mV/m)	Ionospherical Electric Field (mV/m)
1	July 28, 1970	0834-0837	-149.9	-2773	0.29	5
2	July 28, 1970	0839-0841	-208.5	-3857	0.41	8
3	Sept.22, 1970	1047-1056	-165.4	-3060	0.32	6
4	Oct. 12, 1970	0427-0430	-506.6	-9372	0.99	18
5	Oct. 12, 1970	0711-0715	-242.0	-4477	0.47	9
6	Oct. 15, 1970	0802-0805	-150.0	-2775	0.29	5
7	Oct. 15, 1970	0943-0947	-505.7	-9356	0.00	18
8	Oct. 24, 1970	0605-0610	-397.6	-7356	0.78	14
9	Oct. 25, 1970	0729-0733	-611.0	-11304	1.19	22
10	Oct. 25, 1970	0740-0743	-505.7	-9356	0.99	18
11	Nov. 3, 1970	0745-0747	-208.5	-3857	0.41	8
12	Nov. 5, 1970	0838-0842	-1022.0	-18907	1.99	37
13	Feb. 23, 1971	0650-0656	-502.8	-9302	0.98	18
14	Oct. 8, 1971	0331-0340	-513.0	-9491	1.00	19
15	Oct. 8, 1971	0346-0354	-437.5	-8094	0.85	16

TABLE A2 : SUMMARY OF RESULTS (cont'd)

Event No.	Date of Event	Time of Event (UT:=LT+7)	Ionospheric Velocity (m/sec)	Equatorial Plane Velocity (m/sec)	Equatorial Plane Electric Field (mV/m)	Ionospheric Electric Field (mV/m)
16	Oct. 8, 1971	0350-0354	-394.5	-7298	0.77	14
17	Oct. 8, 1971	0445-0455	-321.7	-5952	0.63	12
18	Oct. 8, 1971	0450-0500	-335.2	-6201	0.65	12
19	Oct. 8, 1971	0450-0456	-730.6	-13516	1.43	26
20	Oct. 9, 1971	0250-0256	-620.0	-11470	1.21	22
21	Oct. 9, 1971	0250-0256	-206.7	-3824	0.40	7
22	Oct. 9, 1971	0307-0314	-461.1	-8530	0.90	17
23	Oct. 9, 1971	0313-0330	-225.6	-4174	0.44	8
24	Oct. 9, 1971	0323-0330	-391.7	-7247	0.76	14
25	Oct. 9, 1971	0501-0510	-927.8	-17164	1.81	33
26	Oct. 9, 1971	0652-0702	-900.0	-16650	1.77	33
27	Oct. 9, 1971	0700-0706	-516.7	-9559	1.01	19
28	Oct. 9, 1971	0837-0850	-373.1	-6902	0.73	14
29	Oct. 9, 1971	0901-0905	-487.5	-9019	0.95	18
30	Oct. 9, 1971	0923-0930	-578.6	-10704	1.13	21

TABLE A2 : SUMMARY OF RESULTS (cont'd)

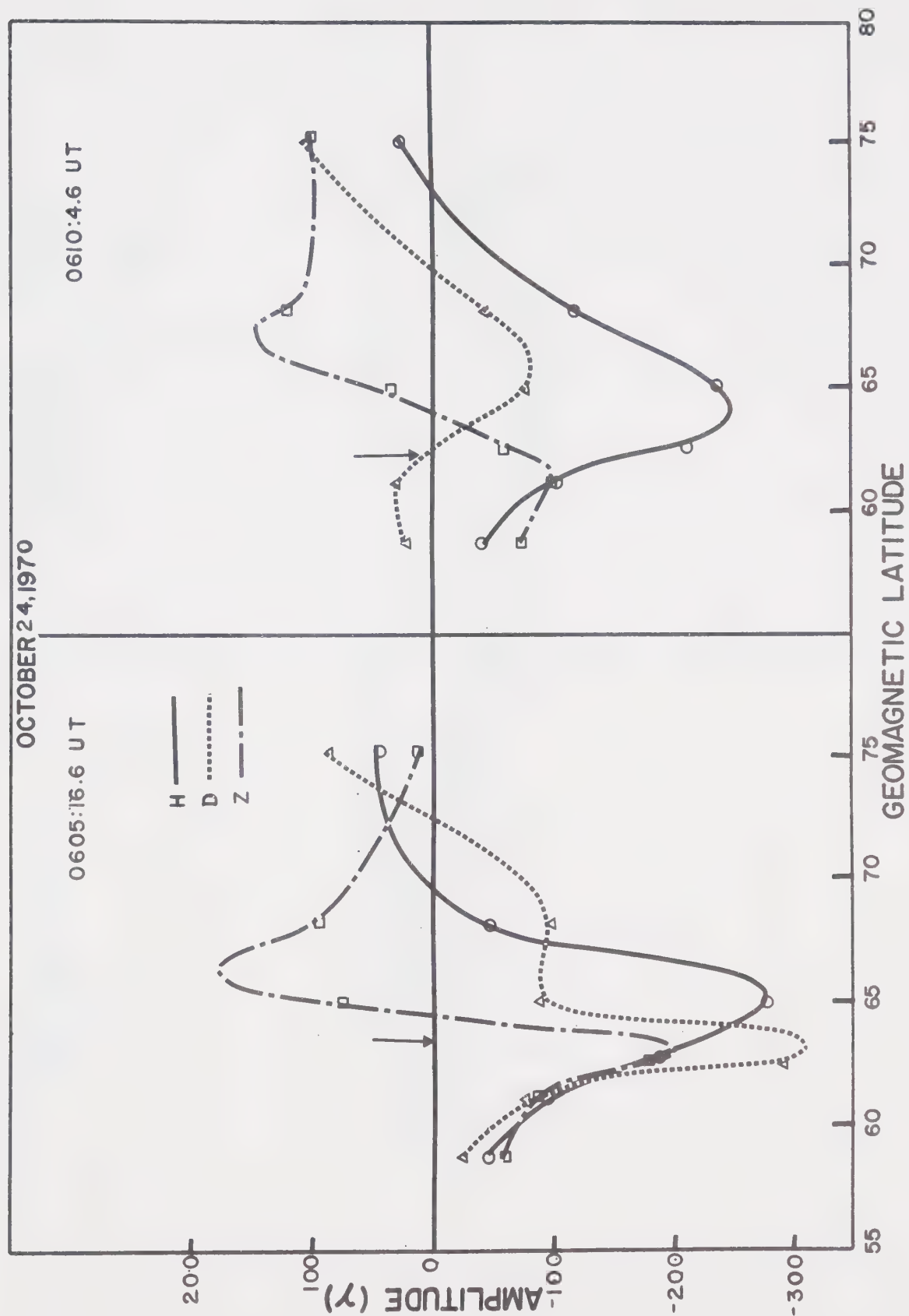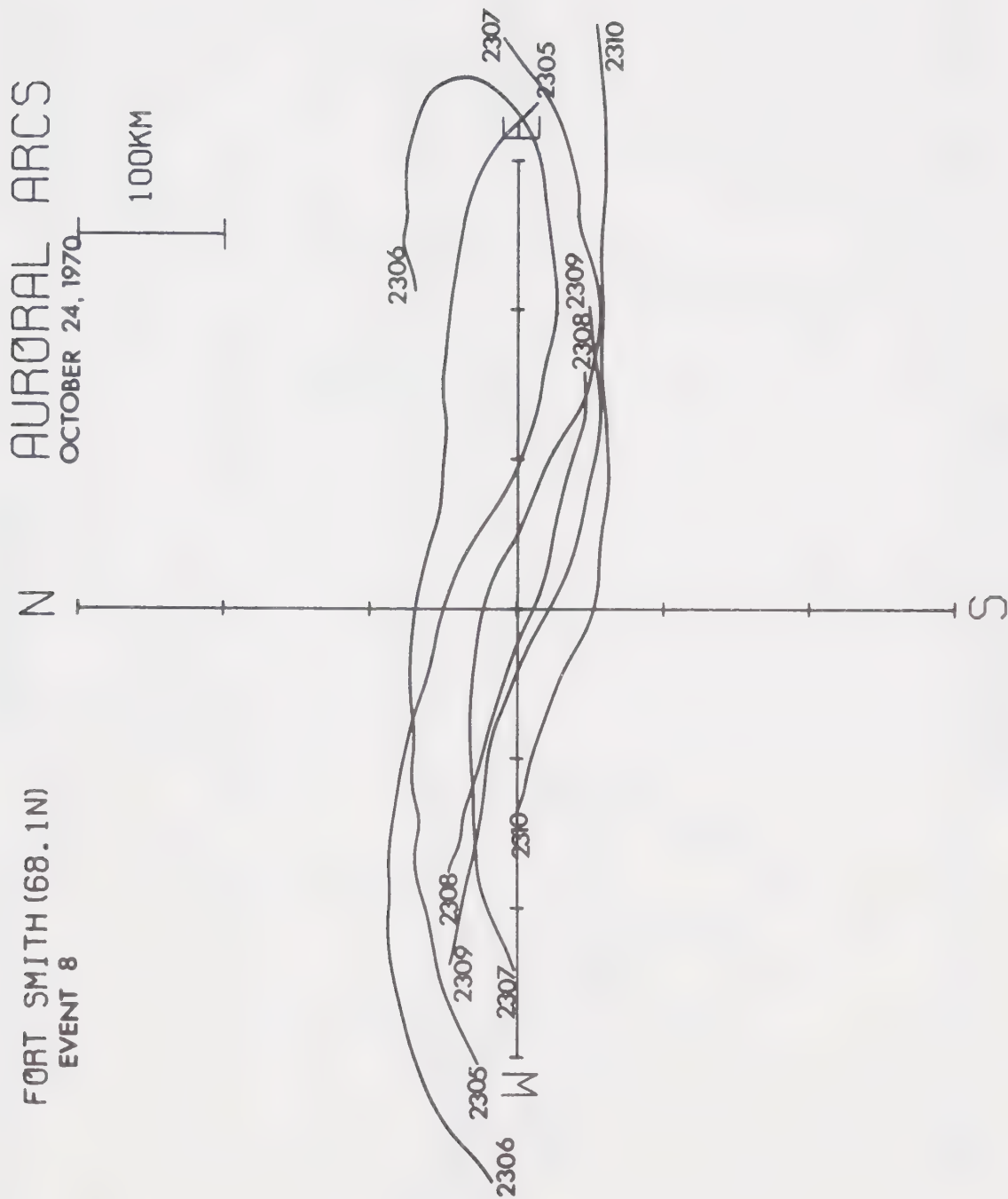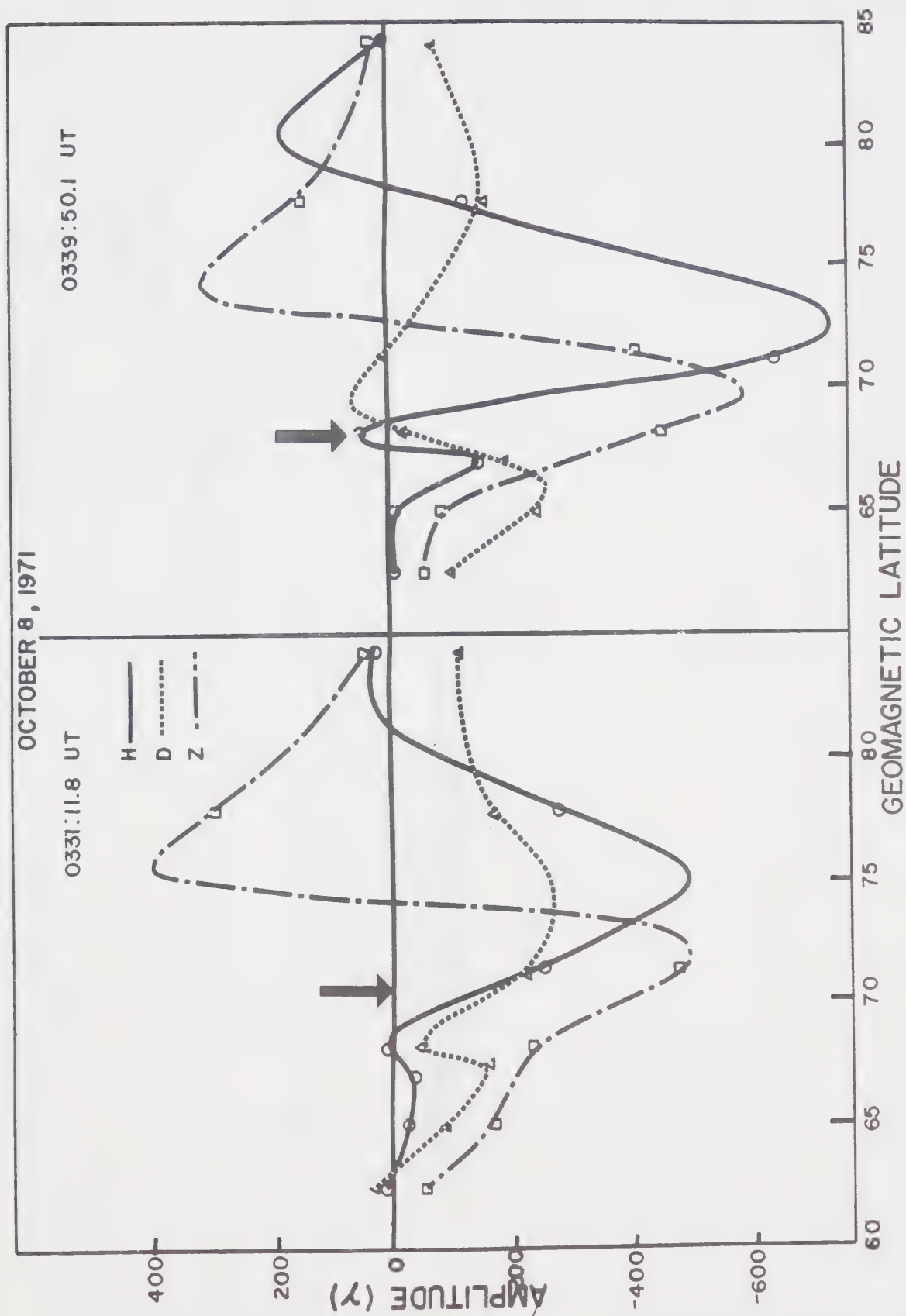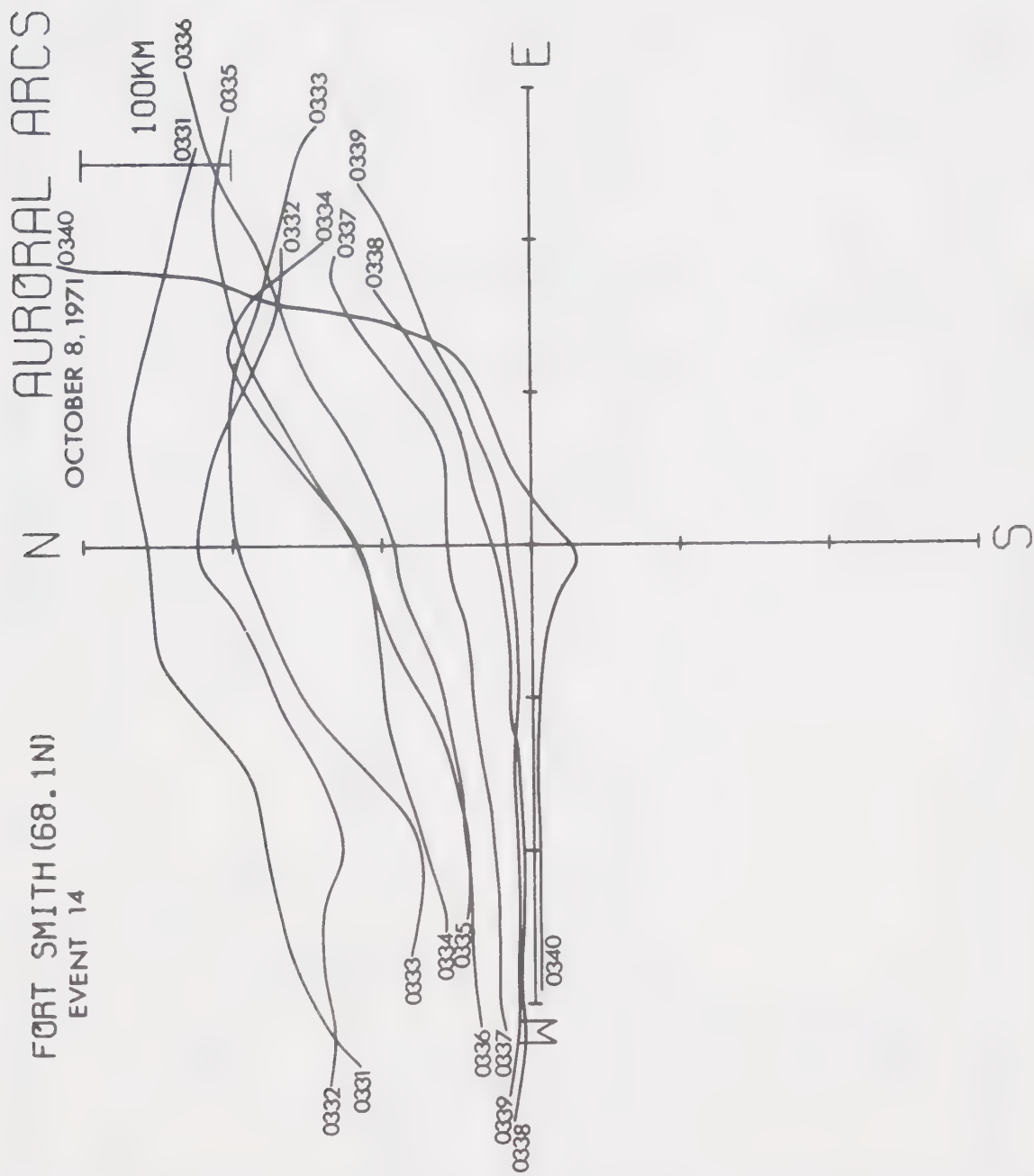| Event No	Date of Event	Time of Event (UT:=LT+7)	Ionospheric Velocity (m/sec)	Equatorial Plane Velocity (m/sec)	Equatorial Plane Electric Field (mV/m)	Ionospheric Electric Field (mV/m)
31	Oct. 9, 1971	1105-1109	-433.3	-8016	0.85	16
32	Oct. 9, 1971	0724-0729	-480.0	-8880	0.94	17
33	Oct. 24, 1971	0535-0545	-715.0	-13228	1.40	26
34	Oct. 24, 1971	0538-0545	-455.6	-8429	0.39	16
35	Oct. 24, 1971	0842-0851	-274.1	-5071	0.53	10
36	Oct. 28, 1971	0920-0926	-502.8	-9302	0.98	18
37	Oct. 29, 1971	0420-0430	-495.0	-9158	0.97	18
38	Oct. 29, 1971	0429-0432	-461.1	-8530	0.90	17
39	Oct. 29, 1971	0434-0438	-305.6	-5654	0.60	11
40	Oct. 29, 1971	0438-0443	-256.7	-4749	0.50	9
41	Oct. 29, 1971	0444-0458	-340.3	-6296	0.66	12
42	Oct. 29, 1971	0456-0505	-247.6	-4581	0.48	9
43	Oct. 30, 1971	0310-0327	-392.4	-7259	0.77	14
Average Values			-440.8	-8156	0.86	16 ± 7

Figure A1a

Figure A1b

Figure A2a

Figure A2b

Figure A3a

AURORAL ARCS
OCTOBER 9, 1971

100KM

N

S

FORT SMITH (68.1N)
EVENT 31

Figure A3b

Figure A4a

AURORAL ARCS
OCTOBER 24, 1971

100KM

FORT SMITH (68.1N)
EVENT 33

Figure A4b